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EMPIRICAL INVESTIGATION ON THE RELATIONSHIP BETWEEN CLIMATE AND SMALL PELAGIC GLOBAL REGIMES AND EL NIÑO-SOUTHERN OSCILLATION (ENSO)

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EMPIRICAL INVESTIGATION ON THE RELATIONSHIP BETWEEN CLIMATE AND SMALL PELAGIC GLOBAL REGIMES AND EI NIÑO-SOUTHERN OSCILLATION (ENSO)

by

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PREPARATION OF THIS DOCUMENT

Recent large-amplitude interdecadal-scale population variations in some of the world's largest fishery stocks have exhibited a remarkable degree of global synchrony. This has been difficult to ascribe to fishing and other direct human interventions. The connotations of large-scale synchronized stock fluctuations for the theory and practice of fishery management, if real, are substantial. Thus the question of the reality of the apparent synchrony looms very large. In an effort to begin to illuminate the mechanisms that could account for such large-scale synchrony, a preliminary exploratory data analysis of evident decadal-scale "regimes" in small pelagic fisheries and of potential causative factors in the earth's global climate system was commissioned by FAO. This document reports results of this analysis.

ACKNOWLEDGEMENTS

This work was developed on the suggestion of A. Bakun, who also offered help and guidance during the course of the study. The activities of Working Group 98 of the Scientific Committee on Ocean Research (SCOR) provided important motivation and background ideas and it is hoped that the concepts and hypotheses generated in this study may in turn contribute to the ultimate findings and conclusions of SCOR-WG98. E. Glazier's editorial work on the English language version is also gratefully acknowledged.

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Empirical investigation on the relationship between climate and small pelagic global regimes and El Niño-Southern Oscillation (ENSO).
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ABSTRACT

El Niño-Southern Oscillation (ENSO) variability is probably the best known mechanism of global climate variability, with large effects on marine ecosystems and particularly on small pelagic populations. However, major changes of small pelagic (abundance regimes) tend to occur on the interdecade scale, rather than with the interannual variability normally associated to ENSO. Despite some recent research, the role of ENSO variability at determining interdecadal climate variations (climate regimes) is still a matter of controversy. In this work, we searched for statistical relationships between small pelagic and climate regimes and ENSO activity, and between these and indices of extratropical and solar variations over the interdecadal time scale.

Climate regimes were detected within the Global Surface Air Temperature record and within other large-coverage air temperature series. Climate regimes seem to be global phenomena although the signal is not equally strong worldwide. A relationship is suggested between climate regimes and El Niño frequency and strength; warm (cool) regimes grossly correspond to periods of few and weak (many and strong) events. Warming (cooling) trends may be characterized as periods of low (high) Southern Oscillation Index (SOI) average values. It is also suggested the change from one regime to another tends to occur when extreme SOI values are reached.

Small pelagic regimes were defined from catch records of the main world fisheries: Japan, California, Humboldt, Benguela and Canary. A composite series (RIS) was constructed. This series is a good indicator of decadal-scale global changes since it tends to emphasize common long-term variability of the stocks while reducing the effects of the individual, year-to-year variations. Comparison between RIS and climate regimes strongly suggests global decadal variability is first evident at the boundary systems of the oceans where small pelagic stocks develop.

For the relationship between the ENSO - as a tropical mechanism - and the Aleutian Low - as a component of the extratropical climate system -, our results suggest that periods of relatively high solar activity tend to promote tropical-extratropical coupling; whereas indenpendent tropical-extratropical variability tends to occur at moderate to low solar activity. Worldwide sardine growing periods (upward RIS trends) seem to occur at moderate to low solar activity. Worldwide sardine growing periods (upward RIS trends) seem to occur when the tropical and the extratropical systems tend to behave independently. Anchovy growing is probably favored by coupled tropical-extratropical interdecal variability.

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1. INTRODUCTION

Many countries and regions, particularly some developing countries, rely heavily on fishery activity for both their economic development and the production of low cost, large quantities of animal protein for human consumption (Weber 1993). The collapse of fisheries often results in severe economic damage and in the loss of many jobs, as well as making infrastructure (boats, plants, harbors, etc.), that in most cases have no alternative use and were developed at a high cost, useless (Weber 1994, Lluch-Belda 1993). Therefore, the prevention of the collapse of fisheries and the optimal use of fishery resources have been both concerns and goals of a large number of management techniques. Approaches have ranged from the purely empirical, adaptive management to the application of population dynamics theory to the definition of maximum sustainable yield and the modeling and prediction of alternative management schemes. Between these two extremes, a number of intermediate levels combining the application of quantitative models with empirical knowledge and management can be found (Walters and Hilborn 1976).

Historically, the first steps towards the development of fishery science came from the experience with large stocks growing in temperate areas and harvested by European countries such as Great Britain. Faced with very complex physical-biological systems, and wishing to predict their variability with only limited information on the system conditions, fishery theory promptly relied on a series of basic assumptions as an attempt towards the consideration of only the major sources of variability but ignoring or assuming as constant some other effects, particularly the environmental (Sharp 1995). Therefore, the first proposed mechanism affecting the abundance of fisheries resources was overexploitation of the stocks, the so-called "fisheries problem". The basic idea was that heavy fishing exerts major predation pressure on the population; this being particular important if pre-spawning fish are affected.

While this simplification enabled the development of a solid conceptual framework and resulted in major advances of the fishery science, nowadays there is increasing evidence that a critical review of those basic assumptions, and particularly the recognition of environmental effects as major sources of variability, is required if fisheries are to be either managed or predicted (Mann and Lazier 1991, Mann 1992). For some fisheries, it has became very clear that the variation of the exploitation level is, by no means, the only significant cause for stock variability (Soutar and Issacs 1969, 1974; Lluch-Belda 1993). Moreover, some studies indicate that even relatively minor changes of climate are likely to result in major and drastic changes in the abundance of some marine species (Sharp and Csirke 1983, Kawasaki *et al.* 1991, Beukema *et al.* 1990).

1.1 Small pelagic regimes

Largely, this recognition has been derived from the experience with the small pelagic stocks. Because they are close to the base of the food web, these species are able to accumulate biomass at their trophic level and to grow into very large populations. Therefore, it is not surprising that their fisheries are by far the most important source of marine biomass for human use, accounting for an average of about a third of the world's total fisheries production. Despite these fisheries having developed in different countries and times, and therefore under very

different management approaches, it has been generally observed that a rapid growing period of a fishery is followed by an unexpected collapse that leaves economic and social disasters (Everett *et al.* 1996). Moreover, paleoecological evidence has shown some small pelagic populations have undergone large changes in their abundance even in the absence of any human exploitation (Soutar and Issacs 1969, 1974; Baumgartner *et al.* 1992).

Sardine and anchovy fisheries have undergone wide changes in their production levels, with sustained periods of high and low catch occurring grossly during the same years in different systems (Kawasaki and Omori 1988, Kawasaki *et al.* 1991, Lluch-Belda *et al.* 1989, 1992). Intensive fisheries of sardine and anchovy are in five regions of the world: the western (Japan) and eastern (California) boundary areas of the North Pacific, the eastern (Humboldt) boundary of the South Pacific, and both the northern (Canary) and southern (Benguela) boundaries of the eastern Atlantic.

A general description of the catch trends in the main systems was provided by Lluch-Belda *et al.* (1989, 1992). Off Japan, sardine catch peaked around 1935, when landings exceeded 1.5 million tons. From the 1940s, however, catches decreased rapidly and only 9,000 tons were caught in 1965. Catches increased again after 1975 and attained over five million tons during the 1980s. Anchovy catch reached maximum levels of more than 400,000 tons in the 1960s and early 1970s, decreasing thereafter during the same period that sardine were increasing. California sardine formed the bulk of the regional catch from the mid-1930s to the mid-1940s. Catches peaked at over 700,000 tons in 1936, but decreased rapidly between the mid-1940s and the early 1950s. They remained low until the mid-1970s when catch off Baja California began to increase. Anchovy catches peaked between the mid-1970s and the early 1980s, with over 340,000 tons taken in 1981. They then decreased to near zero by 1990. A low abundance of sardine off Peru and Chile occurred between 1963 and 1972, thereafter catches increased rapidly peaking near 6 million tons by the mid-1980s. The anchovy fishery started in the 1950s and grew rapidly to more than 13 million tons in 1970, but it then declined very quickly. Finally, off Namibia and South Africa, a sardine fishery started after World War II. Catches increased until 1968 and then collapsed to very low levels by the 1980s. Anchovy were not exploited before the mid-1960s; thereafter catch of anchovy increased concomitant with the decrease in sardine catch.

Lluch-Belda *et al.* (1989, 1992) also noted these changes are more or less synchronous between distant areas, and therefore suggested some global interdecadal phenomenon linking them rather than just the effect of independent fishing pressure. Therefore they proposed the term "regimes" (after the so-called climate regimes) for referring to this scale of small pelagic variability. Small pelagic regimes are thought to be determined by low frequency, long term changes of the climate of the earth. Globally sustained warm periods have had high sardine and low anchovy abundances, while globally sustained cold periods have had high anchovy high and low sardine abundances in the Japan, California, and Peru-Chile Systems (Kawasaki and Omori 1988). The Benguela System seems to be "out of phase" with the others, and shows the opposite pattern of sardine-anchovy abundances (Crawford *et al.* 1987). In any case, the shifts between consecutive abundance levels is often very sharp, with populations growing or collapsing qickly and unexpectedly (Lluch-Belda *et al.* 1989, 1992).

The specific mechanisms linking climate variability and small pelagic regimes are not fully understood even though several suggestions have been made. A general discussion can be found on Lluch-Belda *et al.* (1992a). A first approach towards the explanation of stock variability, as an alternative to the Fishery Problem, stemmed from the early work of Hjort (1914), and has been postulated by a number of authors. It is based on the assumption that the differential survival of the egg-to-larvae stage determines the amount of recruitment, and thus abundance in the following years. Most early papers dealing with this "Recruitment Problem" were reviewed and discussed by Lasker and MacCall (1983), who concluded that, despite the specific mechanism proposed by each author, it is the availability of food that determines larval survival.

Since then, a number of complementary hypotheses have been proposed on some specific mechanisms linking the environmental variability to the differential survival of eggs and larvae, particularly from the experience of the CalCOFI program with the California sardine. MacCall (1986) stated the sardine population growth and intraspecific competition are the main factors that force the expansion of the sardine population. Parrish *et al.* (1981) proposed that offshore advection during intensified upwelling may result in the loss of eggs and larvae to unsuitable areas for growth. Bakun (1990) showed that the intensification of long-term coastal upwelling is observed in several areas, and suggested some consequences for worldwide pelagic fish population (Bakun 1993). Ahlstrom (1965) noted that high productivity (resulting from intensified upwelling) results in poor sardine year-classes, and Lasker (1981) suggested that nonstratified ocean conditions may result in poor survival.

For the Japanese sardine, Kondo (1980) suggested the rapid increase in the stock after 1970 resulted from a very strong year-class, which was caused by a gradual expansion of the spawning area, greater egg abundance, and more favorable conditions for the postlarval stage as a result of a shift of the Kuroshio Current. This current changed from meandering to straight when it was affected by an anomalous southern intrusion of the cold Oyashio Current. This shift in the oceanic circulation created a broad area suitable for copepoda nauplii, thus allowing sardine postlarvae to survive the critical period after yolk absorption. Later, Kawasaki and Omori (1988) proposed that increased solar input may encourage the expansion of the Japanese sardine population by increasing phytoplankton production.

Lluch-Belda *et al.* (1991a, 1991b) proposed a mechanism based in the spawning temperatures and some upwelling-related factor, from their findings that the California sardine population expands its spawning habitat wherever proper sea surface temperature (SST) and moderate upwelling activity occur. Besides temperature, upwelling was found to be an important variable determining sardine spawning, with an optimum value and with sardine avoiding spawning at either too high or too low levels. In a later article, Lluch Belda *et al.* (1992b) suggested that the same mechanism can explain the variability of the Humboldt system stocks. This mechanism implies the major source of recruitment variability is to be found not in the eggs to larvae survival, but on the amount of spawning itself. Both approaches are not mutually exclusive, because climate variations may directly determine spawning, and also modify the egg-survival rate.

Other hypotheses derived from the fact that sardine and anchovy populations, despite many similarities in their ecological and biological characteristics (Parrish *et al.* 1983, Crawford *et al.* 1987, Silvert and Crawford 1988), tend to alternate their abundance periods, with sardines showing high (low) abundance when anchovy population levels are low (high). Therefore, somedegree of exclusive interspecific competition is suspected to occur (Nitba and Harding 1993), although some authors noted that this competition is probably not a major factor (Bakun 1996).

Paleoecological evidence suggests that sardines and anchovies do sometimes grow into large populations within the same decadal periods. Recent comparative studies (Arocena-Ponce-de León, 1996) indicate sardine and anchovy in the Gulf of California show some morphological differences regarding their buccal cavity and filtering structures. From this evidence, the authors proposed one species may feed more effectively than the other on particles of different size, and suggested long-term climate variability may favor one species over the other through this mechanism.

Up to now there has been no agreement among the different authors, although some factors such as food supply, ocean-circulation patterns, changing winds and resulting upwelling patterns, and larval food access as related to turbulence, temperature, and habitat selection have been considered important several times. The difficulty in discriminating among these factors is that they are closely related and mostly change simultaneously. Whatever the specific mechanism through which climatic regimes and abundance regimes may be related, no doubt should remain as to the existence of more than one mechanism as the cause of sardine population fluctuations. However, the relative importance of each of these may be quite different, and a great deal of research must be done to reach definitive conclusions.

Despite the many differing views, most authors agree that small pelagic abundance regimes imply major changes in many characteristics of the ocean physical environment, probably led by shifts of the ocean-atmosphere system (Lluch-Belda *et al.* 1989, 1992). Most authors also agree that the recognition of the environment as a major source of variability does not imply that human (*i.e.* fishery) impacts are to be denied, but rather that both the fishery and the environment act together in a complex and variable way (Everett *et al.* 1996). New and more integrated approaches are to be developed, thus demanding the collaborative effort of scientists with different orientations: fishery, oceanographers, meteorologists, ecologists, physiologists, etc. Such interdisciplinary efforts are currently being done by some international research programs such as SCOR Working Group 98 (SCOR-WG98 1996) and SPACC (Hunter and Alheit 1995).

1.2 Climate variability

Considering the sources of interannual climatic variability on the global scale, nowadays the best described is the ocean-atmosphere interaction known as El Niño-Southern Oscillation (ENSO). ENSO changes are known to have effects on many areas of the earth, and are major phenomena driving ocean climate variability. The following general description of ENSO nature and consequences was extracted from Kassoy (1996).

Major elements of ENSO involve a large-scale redistribution of mass, heat, and momentum within the ocean-atmosphere system, which results in large deviations from climatology of monthly, seasonal, and annual values of temperature and precipitation in many regions of the world. In general, the term ENSO refers to the general system that comprises both warm (the El Niño phase) and cold (so-called La Niña episodes) sea surface temperature extremes of Walker's Southern Oscillation (Diaz and Kiladis 1992). ENSO involves a disruption of the ocean-atmosphere system in the tropical Pacific with important consequences for weather around the globe. Among these consequences are increased rainfall across the southern tier of the USA and Peru, which has caused destructive flooding and drought in the west Pacific, sometimes associated with devastating brush fires in Australia.

In normal, non-ENSO conditions, the trade winds blow towards the west across the tropical Pacific. These winds pile up warm surface water in the west Pacific, so that the sea surface is about ½ meter higher at Indonesia than at Ecuador. The SST is about 8°C higher in the west, with cool temperatures off South America, caused by strong oceanic upwelling associated with trade winds along the equatorial regions and equatorward flow along the South American coast (Enfield, 1989). This cold water is nutrient-rich, and therefore supports high levels of primary productivity, diverse marine ecosystems, and major fisheries. Rainfall is found in rising air over the warmest water, whereas the eastern Pacific is relatively dry.

Every few years (El Niño years), this pattern is broken by periodic heavy rainfall lasting several months, associated with a dramatic increase of equatorial Pacific SST. The weakening of the South Pacific High is accompanied by a decrease in the strength of the trade winds, and the resulting weakening of the oceanic upwelling causes the SST to rise in the Eastern Tropical Pacific.

This warming of the ocean surface causes increased evaporation and heating of the surrounding troposphere and decreased atmospheric stability, creating conditions favorable for convection and rainfall. This process tends to be self-sustaining because the development of organized areas of convection near the equator tends to further weaken the trade winds within and to the west of the convection area, thereby causing SSTs in that area to remain anomalously warm. Forcing mechanisms of El Niño events are caused by a complex ocean-atmosphere instability that depends on the coupling of the two media (Díaz and Kiladis, 1992).

Another aspect of ENSO is the state opposite to El Niño, the so-called La Niña or cold event. During this phase, the climatological conditions of heavy rainfall over the monsoon regions and relatively cool SST over the Eastern Equatorial Pacific are amplified. The global-scale climatic anomalies during cold events are for the most part opposite in sign to those seen during warming events.

The direct impacts of an ENSO warm phase (El Niño) come in many forms, from storms and subsequent damage in the western United States as a result of changing weather patterns, to a disappearance of fish along the Peruvian coast. For example, the collapse of the Peruvian anchoveta has been blamed on the 1972 El Niño event. According to this idea, this significantly disturbed the cycle of upwelling along the coast, changing the ecological systems of the region.

Instead of temperate water rich in nutrients, a wave of nutrient poor, warm water moved toward the coast, creating an environment unable to support the existing marine life (Cavides and Fik 1992).

Some authors have suggested that, just as the marine habitat was disrupted in South America as a result of the 1972 El Niño, the 1982-83 event altered the abundance of salmon in the US Northwest. The size and availability of coho and chinook salmon experienced reductions along the Washington, Oregon, and California, and the Fraser River, while sockeye migrated north into Canada. Extratropical effects of the very strong 1982-83 event contributed to the largest diversion in recent history of these sockeye into Canadian waters (Miller and Fluharty 1992).

However, ENSO changes are often regarded as high frequency, year- to- year variations, whereas the most significant changes of the pelagic stocks and their environment are believed to occur over the interdecadal -regime- time scale. The possible relationships between the ENSO cycle and the regime changes are not fully understood. Among the early suggestions, Bakun (pers. com.) proposed that regimes might be characterized as sustained periods of high-low ENSO activity, thus providing a link between them. Extending this idea, high(low) ENSO activity periods may be regarded either as periods with many (few) El Niño-La Niña events, periods of strong (weak) events, or as a combination of both. Similarly, regime shifts may somehow be triggered by very strong El Niño-La Niña events.

Climatic changes on the interdecadal scale have been the subject of several recent studies, particularly since it is necessary to understand the natural variability over this time scales before the proper assessment of the possible effects of the global warming can be achieved. Among the best documented cases, Beamish (1995) showed that a sudden, worldwide shift during 1976-1977 can be observed in many time series, including both atmospheric and oceanic variables (Trenberth 1990, Graham 1994, Meyers *et al.* 1996). At the biological level, this change of the system was experienced both by some exploited populations (Francis and Sibley 1991, Francis and Hare 1994, Drinkwater *et al.* 1996) and by others not under direct anthropogenic influence (Roemmich and McGowan 1995, Polovina *et al.* 1994, 1995). Though the origin of the 1976-77 shift is not clear, some authors believe this climatic event should not be considered an isolated phenomenon but rather an extreme phase of natural oscillations of the climate systems occurring in periods of 16 to 24 years (White and Cayan 1996).

Many workers have dealt with the possible causes of climate change over this time scale but it remains unclear whether the nature of the causes is atmospheric or oceanic, and both atmospheric forcing (Miller *et al.* 1994, Graham 1994) and changes in the depth of the ocean mixed layer (Polovina *et al.* 1995, Polovina 1996, Meyers *et al.* 1996) have been mentioned. Despite some major advances, no consensus has been reached yet. Some authors (Jacobs *et al.* 1994) have proposed that interdecadal variability is driven by the tropical system through ENSO-related mechanisms. Others believe this mechanism is likely to be found at the interaction between the tropics and the extratropics, and even others have proposed that interdecadal climate variations are basically extratropical phenomena.

Graham (1994) suggested that climate oscillations over the interdecadal time scale may be caused in the Tropical Pacific by particularly strong El Niño events that have extended and

prolonged extratropical effects. These prolonged effects are believed to arrive via reflected Rossby waves generated when the ENSO-related tropical Kelvin waves reach the eastern boundary of the Pacific basin. Modeling and sea level variations suggest that after the reflected Rossby waves reach the western boundary, they promote a northward shift in the direction of the Kuroshio Current extension; these in turn force higher than normal sea surface temperatures over the northwest Pacific for periods longer than a decade (Jacobs *et al.* 1994).

Similar results were obtained by Latif and Barnett (1994, 1996) from their study of the effects of the seasonally varying insolation integrated over 70 years, by means of a coupled model of global ocean-atmosphere general circulation (ECHO). Their results show a 20 year cyclic signal on the heat content of the surface layer over the Northwest Pacific, the signal being stronger over the Kuroshio Current extension. Simulated sea surface temperature in this region showed an irregular oscillatory behavior on the decadal time scale. The model also showed that positive and negative anomalies change their relative position in a pattern that reminds one of the North Pacific Gyre, completing a cycle after 20 years. The authors claimed this variable pattern of the position of the anomalies may in turn result in changes of the subtropical gyre strength, therefore providing a positive feedback and accounting for the observed cyclic behavior.

However, a major difference between this mechanism and that proposed by Graham (1994) is embodied in the fact that Latif and Barnet (1994, 1996) obtained similar results even when the information on the tropical Pacific variability was excluded from the model, thus suggesting the actual mechanism is not ENSO related. Similarly, White and Cayan (1996) suggested the 20-year oscillation of the North Pacific sea surface temperature is to be explained by the poleward migration of the Aleutian Low and the resulting intensification of the extratropical wind fields. The 20 year signal is detectable not only at the surface but through the upper 100 to 200 m of the ocean as previously suggested by Polovina *et al.* (1995) from the identification of this signal in the variations of the mixed layer depth and also in some indices of marine biological production.

The debate is still ongoing, and has been enriched by other authors who searched for tropical-extratropical interactions as the origin of interdecade variability. Ghil and Vautard (1991) used time- series analysis of global and regional air temperature records, and found that significant cyclic components occur both over interannual, ENSO-like periods (5 to 6 years) and interdecadal periods (16 to 21 years). They suggested a tropical nature for the former and a extratropical origin for the latter. More recently, Zhang *et al.* (1996) worked on an ENSO-like EOF (Empirical Orthogonal Function) mode in the SST global field and were able to separate two components, one identified with the ENSO variability, but the other being linearly-independent residuals comprising all the decade-to-century variability and exhibiting a larger amplitude over the extratropical North Pacific.

From the above, it seems clear this line of research is just starting and a lot of future work will be required before the causes and mechanisms of the interdecadal variability can be agreed upon, particularly regarding the linkages between the physical and the biological systems that are in the very nature of the small pelagic regimes. Therefore, the purpose of this contribution is only to provide additional evidence on the relationship between interdecadal regimes, both climatic and biological, and the ENSO as the best-known source of the variability of interannual global

climate. Despite the approach being largely empirical, we hope that some of the results will be useful towards the long-term goal of explaining the causes of small pelagic world-wide fluctuations.

The work has been divided in two main parts. In the first, we deal with those results concerning the analysis of the global climate regimes as identified within the GSAT series. Global climate regimes are then compared to large-coverage air temperature series, to define wherever identified regimes should be considered truly global phenomena. Then, we present some evidence regarding possible linkages between global climate regimes and ENSO activity. The second part deals with the small pelagic regimes, as defined from the catch records of the main sardine and anchovy fisheries. Small pelagic regimes and global climate regimes are then compared. Evidence is presented concerning the possible relationships between small pelagic regimes and interdecadal tropical and extratropical variability. Some connection to decade-scale solar activity variations is also suggested. Finally, suggestions are made regarding possible connections between global small pelagic regimes and regional climate variability in those areas where large sardine and anchovy stocks occur.

2. DATA AND METHODS

One problem regarding regime period definition as given by Lluch-Belda *et al.* (1989, 1992) is that sardine and anchovy stocks over the world, although fluctuating during the same gross periods, show year to year differences between areas which make it hard to establish when a given global regime starts or finishes. One reason for this is that stock abundances must be inferred from catch data, since more accurate indices of abundance are lacking for all areas and periods. While this is not a problem in demonstrating the existence of regime changes, the characterization of regime periods in terms of the ENSO phenomenon requires these periods to be defined as accurately and objectively as possible.

We first approached the problem using the annual global air surface temperature (GSAT) to build an "index" of global climate regimes, keeping in mind that sardines tend to be abundant during sustained, long-term high-temperature periods and anchovies are abundant during sustained, long- term low-temperature periods (except for the Benguela System, where the opposite situation seems to be the case). A second approach was to build a composite series for the sardine and anchovy regimes. This will be explained later.

GSAT series, as made available by the NCAR/NWDC/NOAA, is presented in Figure 1. This series consists of yearly anomalies computed as departures from the 1951 to 80 year average. Since regime variability is over the decadal time scale, some transformations have to be made to these data before they are evident. First, the series shows a clear long term upward trend which should be removed, since we are not interested in this time scale

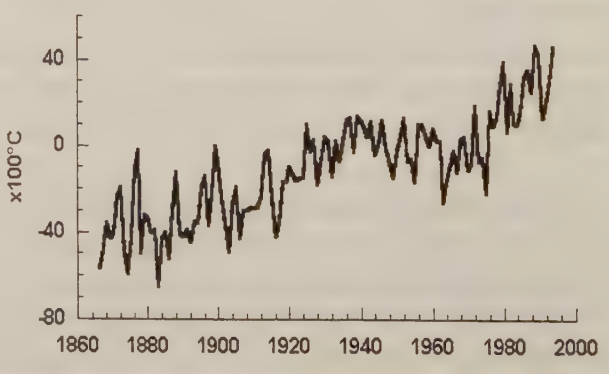


Figure 1. Global Surface Air Temperature (GSAT)

variability. Similarly, the high frequency should be removed for the same reason. Finally, the period considered for computing the average year temperature implies that the average of the entire series is not zero, which makes it difficult to classify the years as either warm or cold. To avoid these problems, the original GSAT series was first detrended by substracting the simple regression line and then smoothed by means of the following simple exponential transformation:

$$S_t = 0.1*X_t + (0.9)*S_{t-1}$$

where S_t is the value of the transformed series at time t, and S_{t-1} is the value of the transformed series at time t-1, X_t is the value of the untransformed series at time t. Finally, data were standardized to make the average value equal to zero. To show the correspondence between climate regime periods as identified within this series and those shown by the small pelagic catch, Tables 1 and 2 (page 14) present a synthesis of the sardine and anchovy regime periods as identified by Lluch-Belda *et al.* (1989, 1992).

For the analysis of the spatial coverage of the climate regime signals, we used the large coverage air temperature series provided by the NCAR/NWDC/NOAA. These are 12 series of yearly mean air temperature, grouped into three spatial resolution levels. The first level includes two series, one for each hemisphere, which will be referred as NH and SH. The second level includes three series for the following latitudinal bands: 24 to 90N (referred as N1), 24S to 24N (referred as E1) and 24 to 90S (referred as S1). The third includes the following eight latitudinal bands: 64 to 90N (N11), 44 to 64N (N12), 24 to 44N (N13), 0 to 24N (N14), 0 to 24S (S11), 24 to 44S (S12), 44 to 64S (S13) and 64 to 90S (S14). For comparison to the identified regime trends and periods, these series were treated the same way as the GSAT was (i.e., detrended, smoothed and standardized).

To test the relation between each area and the global regimes, we computed the correlation coefficients between the eight latitudinal bands and the transformed GSAT, for 1904 to 1995. Before doing this, normality was tested for all the series using the Shapiro-Wilks W test. All series were found to behave normally except N11, thus its correlation coefficient is not to be considered.

For the analysis of El Niño events, we built series of relative strength and frequency content of interdecadal variations, based on the 20th Century data of years in which large-scale El Niño events occurred, as stated by Quinn (1992). These include not only the year in which the event started, but also a gross estimate of its strength based on different sources of historical evidence (see Quinn *et al.* 1987, Quinn and Neal 1992 and Quinn 1992).

To show some possible changes in the frequency of events over the interdecade time scale, the number of events were summed over moving 11- year periods. A similar process was applied to the relative-strength data, using zero for those years in which no event started. Because each event is associated with the year in which it started, it is considered only once regardless of its duration.

These data were smoothed and then compared to the periods identified within the transformed GSAT series. The unsmoothed frequency and strength values were also grouped by

the two periods defined from the transformed GSAT series and distributions for each period were carried on. When looking for differences between these periods, we used a Kolmogorov-Smirnov two-way mean comparison, since their distributions proved to be non-normal. Correlations between the transformed GSAT and all the unsmoothed frequency and relative strength data were determined after successfully testing the three variables for normality by means of the Shapiro-Wilk W-test.

Since the GSAT series consists of annual means, statistical comparisons between this series and the monthly Tahiti-Darwin SOI series was difficult. Therefore, we looked at the correlations between SOI annual and seasonal means series (as computed from the monthly values), in order to define which series were to be compared against the yearly GSAT series. As can be noted (Figure 12), there are close and statistically significant correlations between the yearly averages (YR) and all seasonal series except winter (W), which varies rather independently of the others. Thus, we decided to use both the yearly mean series (as representative of the SOI variations from spring through fall) and the winter series. For this last series the SOI value for December of the preceding year was used when computing the seasonal average.

One additional problem when trying to analyze the ENSO variability is that all the available time series (Tahiti-Darwin, Australian, COADS-derived, etc.) show some gaps during the present century. However, they are not for the same periods in all of the series, and since the different indexes are usually well correlated, it is possible to combine them to build a continuous time series. Therefore, we correlated the Tahiti-Darwin SOI to the COADS SOI, and used the regression equation to "fill the gaps" by calculating the missing values of the first series from the observed values of the second series. This procedure allowed us to complete most of the missing values. However, a two years gap (1914 and 1915) persisted because the COADS SOI index has no observations for those years. Because this is a minor gap, those values were interpolated within each series. The resulting "composite" SOI series is almost continuous for the present century.

We present the "composite" yearly and winter SOI series (see Figure 14), with both the original and the transformed values (*i.e.* 9-terms moving average smoothed, detrended and standardized). We calculated regressions between SOI (winter and yearly) and GSAT series as well as distributions of the transformed SOI series (yearly and winter) grouped by the trends and periods previously detected in the GSAT.

SOI is considered as an index of ENSO activity at the interanual time-scale. Positive values indicate that atmoshperic pressure at the western tropical Pacific Ocean is above that of the eastern side. Conditions when this situation is revert, and the SOI becomes negative, are indicative of an ENSO event. However, relations at decadal time-scale are not so direct and thus not as well stablished and understood. Since our research focuses on regime time-scale variability, we have explored this relation by plotting together the series of frequency and strength of ENSO events with two series derived from the SOI: the 11 years moving average of yearly SOI values and a series of the positive to negative rate of SOI yearly values over periods of 11 years.

One problem regarding the sardine and anchovy abundance regimes as defined by Lluch-Belda *et al.* (1989, 1992) is that different stocks, although they fluctuate grossly simultaneously, do show some differences in timing from one region to another. At least to some extent these variations result from different fishery regimes. Therefore catch records, while they may be regarded as a gross index of large abundance changes, are by no means precise indicators of abundance changes, particularly of the year-to-year variability. Thus, when looking for correlations between worldwide abundance fluctuations and global climate series it is necessary to build one "composite" series that reflects the gross global tendencies rather than the regional short-term variations.

We approached this problem by combining the catch records of the main sardine and anchovy fisheries as provided by SCOR WG-98 (1996); those of the Japan, California, Humboldt, Benguela, and Canary systems. Individual annual catch series were first standardized and then summed as follows:

$$RIS = (JS+CalS+HS+BA+CanS) - (JA+CalA+HA+BS+CanA)$$

where:

RIS: Annual composite value of the regime indicator series
JS: Standardized annual catch of the Japanese sardine
JA: Standardized annual catch of the Japanese anchovy
CalS: Standardized annual catch of the California sardine
CalA: Standardized annual catch of the California anchovy
HS: Standardized annual catch of the Humboldt sardine
HA: Standardized annual catch of the Humboldt anchovy
BS: Standardized annual catch of the Benguela sardine
BA: Standardized annual catch of the Benguela anchovy
CanS: Standardized annual catch of the Canary sardine
CanA: Standardized annual catch of the Canary anchovy

As defined, RIS values are highly positive when sardine stocks worldwide are abundant and anchovy stocks are at low levels, while strong negative RIS values are indicative of the opposite combination of abundance levels. The Benguela stocks were summed differently than the others. Benguela sardine (anchovy) catches were added to the anchovy (sardine) catches of the other systems. By doing so, we followed Crawford *et al.* (1991) and Lluch-Belda et al. (1989, 1992), who noted the Benguela stocks fluctuate "out of phase" with the rest of the stocks.

To investigate the relationships between RIS regimes and variability of the tropical-extratropical climate, we used the SOI composite series (yearly) and the Aleutian Low normalized November to March sea level pressure series (AL), after Polovina *et al.* (1995). Both series were smoothed by means of a 7-year moving average filter to eliminate the high-frequency variability, and then standardized for comparisons.

Relations to solar activity were investigated using the series on yearly sunspot numbers as provided by the Sunspot Index Data Center, Royal Observatory of Belgium. To eliminate variability not on the decadal-scale, the original data were detrended, smoothed with an 11-year moving average filter and scaled as departures from the average value. The 11-year signal of the original series was removed (on purpose) because of the selected filter. We have compared this series with the absolute differences of the SOI-AL by simple linear correlation.

Small pelagic regimes, as identified within the RIS, were used as reference periods when looking for the interdecadal variability of the following selected marine ecosystems: California, Japan, Humboldt, Eastern Australia, Eastern Tropical Pacific, Brazil, Canary, Benguela, and Somali. For each of these regions, a 10x10° box was selected, and their climatic information extracted from the following databases: sea surface temperature and sea level pressure from the COADS-CD ROM (Roy and Mendelssohn 1994) and temperature profiles from the NODC-CD ROM (NODC 1991). Selected areas are shown in Figure 2.

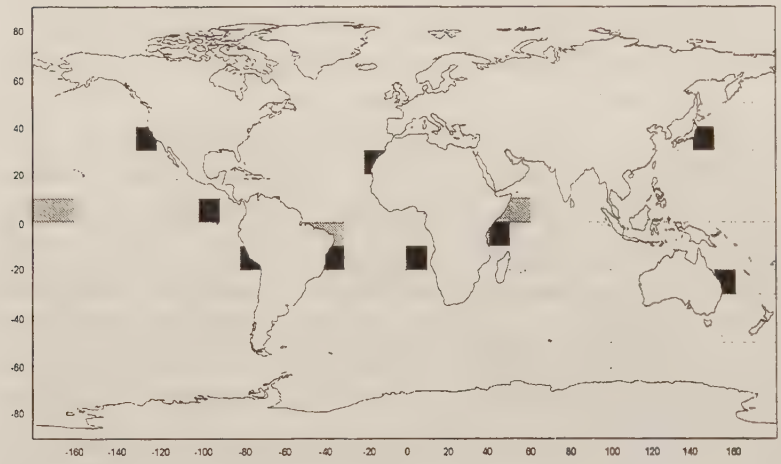


Figure 2. Selected 10x10° boxes for the computation of regional climatic series (dark shaded), and tropical areas selected for computing of the pressure gradients (light shaded).

For each area, individual SST observations were averaged to generate a monthly time series for 1900 to 1990 period. Seasonal climatology values were computed for this entire period. Then, the same procedure was performed but for the following selected periods: 1941 to 1961 (a period of small SOI-AL differences, see Figure 20) and 1971 to 1977 (a period of high SOI-AL differences). Departures of each period values were also compared to the overall climatology.

A similar treatment was applied to the pressure data, except that the monthly series of each system (Figure 2, dark shaded boxes) were first substracted from a similar series built for the tropical areas within each ocean (Figure 2, light shaded boxes) to build individual pressure indices. These are intended to reflect the variations of the pressure gradient within each system.

Temperature profiles were first averaged for each selected area on a monthly basis, and the resulting values used to build a monthly time series of thermocline depth, estimated as the mid-depth of the layer where the maximum change of temperature per unit depth takes place. The resulting series were then used to estimate the seasonal climatology values and the seasonal averages for the selected periods, as previously defined for the sea surface temperature.

3. RESULTS AND DISCUSSION

As previously mentioned, the work is divided in two main sections for presentation purposes. The first section (3.1) deals with the analysis of the climate regimes and their possible connections to interdecadal ENSO variability. The second section (3.2) is dedicated to the definition and analysis of small pelagic regimes. Finally, an integrated view of the relation between climate and small pelagic regimes is attempted.

3.1 Global climate regimes

In this section, results of the analysis of the global climate regimes are presented and discussed. First, we show that climate regimes are detectable as the interdecadal variability of the GSAT series. Regime periods, as identified within this series, are compared to decadal signals of other large-coverage air temperature series. Finally, the same periods are used to show variations of the frequency and relative strength of ENSO events and of the long-term trends within the SOI.

3.1.1 Identification of global climate regimes

Figure 3 shows the detrended and smoothed GSAT series. Sustained warm-cold periods, sustained long-term trends, and wide fluctuations are evident only during the final part of the series (P2, solid line). Before 1918 (P1, broken line) the variability is lower, as no value reaches one standard deviation positive nor negative. Cooling-warming trends and cold-warm periods are shorter that those after 1918, which may indicate that before this year the global climate variability was dominated by phenomena of a shorter frequency than regime changes (at least, shorter than the documented regimes of abundance fluctuations of sardine and anchovy). Given that small pelagic regimes are only documented for the present century, we decided to focus only on the second period (P2). This is not to say that possible relationships between interdecade variability, ENSO variations, and small pelagic abundances do not exist before 1918, but the current lack of evidence of small pelagic fluctuations makes it difficult to evaluate them for those early years.

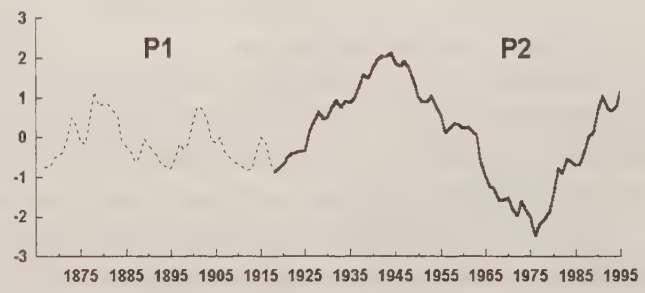


Figure 3. Detrended, smoothed (simple exponential transformation), and standardized GSAT series.

After 1918, three sustained long-term trends are evident from the transformed series (see Figure 4). The first is a 27 year upward-trend that lasted until 1944, which happens to be the year with the highest positive difference from the long-term trend line. Then, a sustained downward trend took place until 1976, the year with the largest negative deviation. Finally another upward trend goes to at least 1995. Between these long term trends, sustained periods of positive (warm) and negative (cold) anomalies are also evident. From 1926 until 1963 values are positive, the period between 1946 and 1987 is one of negative values, and since 1988 values have been positive again.

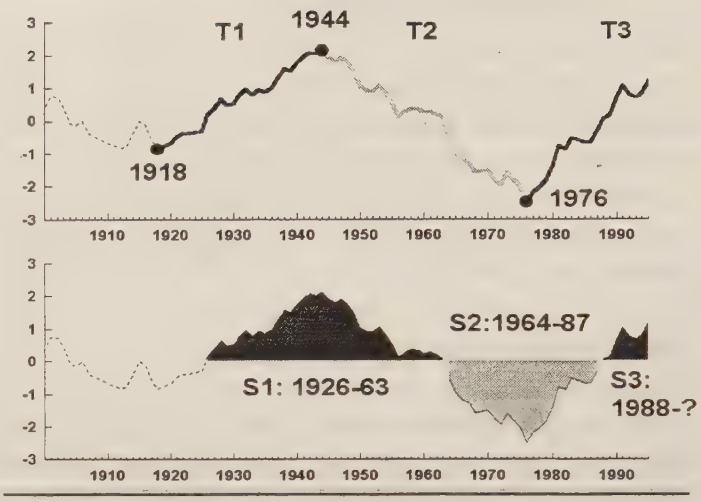


Figure 4. Upward (T1, T3) and downward (T2) sustained trends (upper panel) and sustained periods of warm (S1, S3) and cold (S2) anomalies as reflected by the GSAT transformed series.

Tables 1 and 2 show these periods and trends together with the abundance fluctuations of the main sardine and anchovy stocks. Broadly, it can be noted the warming trends have coincided to periods when sardine (anchovy) abundance increases (decreases), and the warm periods include several years of high (low) sardine (anchovy) abundance. Similarly, cooling trends generally coincide with increasing (decreasing) anchovy (sardine) abundance, and cool periods include several years with large (small) anchovy (sardine) population levels. This scheme is particularly evident for the California area, and generally applicable to the Japan and Humboldt Systems. Allowing for the opposite species arrangement, the Benguela sardine is also in general agreement with the mentioned scheme, and only the Benguela anchovy seems to behave in a different and unique way.

Table 1. Regime-related periods and trends and abundance variability of the main sardine stocks. Abundance trends as described by Lluch-Belda et al. (1992), except: (1): All years above 100 MT except 1953, according to data from Barnes *et al* 1992. (2) See Smith 1990. (3) See Barnes *et al.* 1992. (4) Implies biomass in excess of 18,000 MT.

Period	California	Japan	Humboldt
1918-44 Warming trend	Catch increased (1916-36)	Catch increased (1915-36)	No data until early 1970s, since a significative fishery started after the collapse of the anchovy stock.
1926-63 Warm period	High catches during the 30s and 40s. High spawning biomass off California up to 1960[1]	High catches from mid 1920's to mid 1940's, but decreasing since late 1930's.	
1944-76 Cooling trend	Catch decreased (1945-60). Spawning biomass off California decreased rapidly on 1941-53[2].	Already scarce, remained low until 1975.	
1964-87 Cold period	Low catches since 1952 Spawning biomass remained low during 1966-86[2].		
1976-onwards Warming trend	Increasing trend of sardine biomass since late 1970s[3].	Catch increased during 1975-88.	Catches increased (1977-1988), and spawning biomass since 1974 until 1982.
1988-onwards Warm period	Direct fishery allowed since 1986 [4].	High catches during 1981-91, but decreasing since 1989.	High catches (1984-1991), but decreasing since then.

Table 2. Regime-related periods and trends and abundance variability of the main anchovy stocks. Regime-related periods and trends and abundance variability of the main sardine stocks. Abundance trends as described by Lluch-Belda et al. (1992), except: California biomass data kindly provided by A. MacCall for SCOR WG98. (2) South Africa biomass data kindly provided by R. Crawford for SCOR WG98.

Period	California	Japan	Humboldt
1918-44 Warming trend	No data available	Low catches until late 1950's, with no evident sustained trend.	No data available
1926-63 Warm period			
1944-76 Cooling trend	Biomass rapidly increased on 1969-74.	Catches increased during 1946-56.	Catches increased during 1960-1970
1964-87 Cold period	High biomass during 1974-86. High catches until 1989.	High catches during 1954-72.	High catches during 1962-71.
1976-onwards Warming trend	Biomass decreasing since 1976, catch decreasing since 1981.	Catches decreased during 1973-89.	Catches decreased during 1972-84.Lowest catches during 1977-85
1988-onwards Warm period	Biomass lowest values since 1989.	Low catches during 1977-89, increased for 1990.	Rapidly increasing since 1986

3.1.2 Global climate regimes as reflected by wide-coverage air temperature series

For the identified climate regime trends and periods, it is important to establish whether these are earth-scale signals or just regional phenomena. The fact that regimes are evident from the GSAT series cannot be considered as definitive evidence, because this series averages all the available observations, thus implying very different spatial and temporal coverages. The ideal way to establish the spatial coverage of the regime signal would be to analyze temperature series from small areas, but only a few can be calculated back in time to make the analysis possible. Therefore, the use of series averaged for large areas is usually the only possibility for building time series long enough to reflect regime variations.

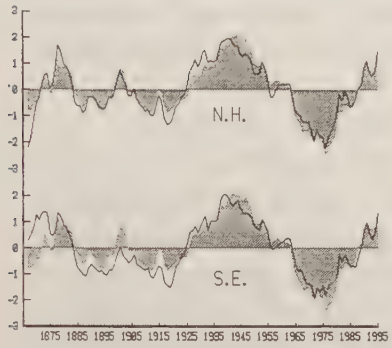


Figure 5. Detrended, smoothed (simple exponential transformation), and standardized Surface Air Temperature (solid lines) for the northern hemisphere (upper graph) and southern hemisphere (lower graph) series and transformed GSAT series (area).

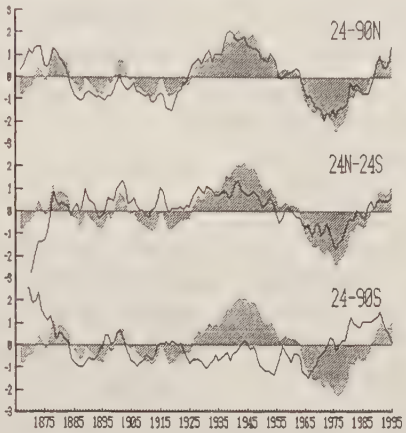


Figure 6. Detrended, smoothed (simple exponential transformation) and standardized Surface Air Temperature series (solid lines) for three latitudinal bands (24°N to 90°N: N1; 24°N to 24°S: E1; 24°S to 90°S: S1) and transformed GSAT series (area).

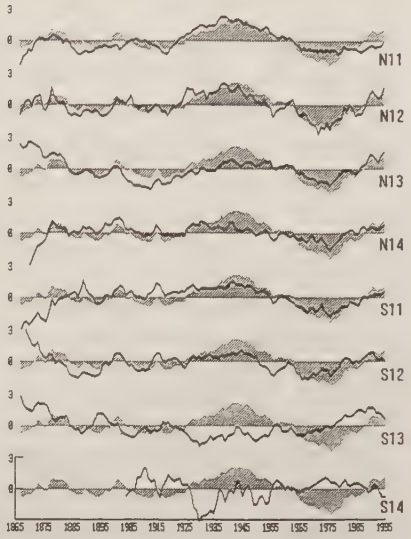


Figure 7. Detrended, smoothed (simple exponential transformation) and standardized Surface Air Temperature series (solid lines) for eight latitudinal bands (64°N to 90°N: N11; 44°N to 64°N: N12; 24°N to 44°N: N13; 0° to 24°N: N14; 0° to 24°S: S11; 24°S to 44°S: S12; 44°S to 64°S: S13; 64°S to 90°S: S14) and transformed GSAT series (area).

Figures 5 to 7 show the NCAR large-coverage air temperature series (solid line), together with the transformed GSAT series from Figure 3 (light area). The GSAT trends and periods are evident on the hemispheric scale, both at the north and the south (Figure 5). At the second level of spatial resolution, regional differences become noticeable (Figure 6). Trends and periods are still well defined in the northern area, but are less evident at the equatorial band and not evident at all in the southern region. The third level of resolution (Figure 7) allows us to confirm that the regime signal of the GSAT (i.e. much of the interdecade variability of the GSAT) is more evident

at the northern than at the southern areas: southward 24-44S (S12), series show a totally different behavior compared to the GSAT. Moreover, interdecade temperature variation in one of these areas (S14) seems to have an inverse relationship to the global thermal regimes.

Correlation coefficients between the series shown on Figure 7 and the transformed GSAT, for 1904 to 1995, are in Figure 8. When analyzed *versus* the GSAT, most areas proved to be significantly correlated. However, the statistical relation rapidly weakens southward 44 to 64N and at 44 to 64S (S13) is not significative. Even further south (64 to 90S, S14), the relation becomes significant again but changes sign, thus indicating an inverse relationship. Therefore, results suggest that during the present century the regime related periods, as defined within the GSAT, have been coherent on the global, hemispheric, and regional (here, wide latitudinal bands) spatial scales. However, the signal power is different between regions: north of 44S, it is strong, but southward it becomes weak. Finally, the two possibilities of relationship between global and regional regimes have been observed; northern regions show a direct relationship, while the southernmost region is inversely related.

Figure 8. Correlation coefficients and simple regression lines between eight latitudinal SAT bands (64°N to 90°N: N11; 44°N to 64°N: N12; 24°N to 44°N: N13; 0° to 24°N: N14; 0° to 24°S: S11; 24°S to 44°S: S12; 44°S to 64°S: S13; 64°S to 90°S: S14) and transformed GSAT.

3.1.3 Climate regimes and El Niño relative strength and frequency

From Figure 9, it is evident that both the frequency and the strength of ENSO events have varied during the present century. For 11 year periods, the frequency of events has changed from 0.18 to 0.45 events per year, while the average strength goes from 0.8 to 2.2. This variability is not totally random in time. Despite some mid-term variations, both frequency and strength show long-term trends similar to those identified in the transformed GSAT series.

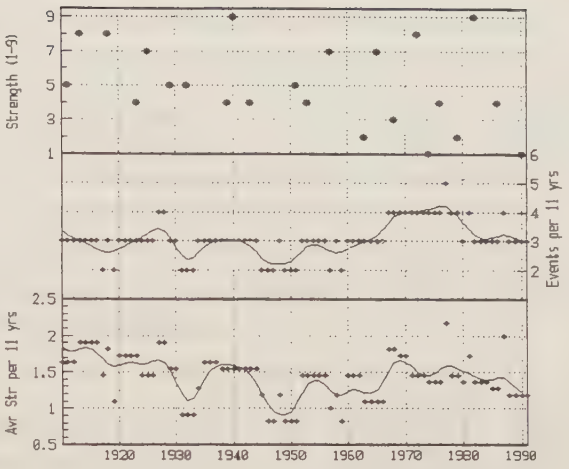


Figure 9. Upper panel: Series of years and relative strength (very weak: 1 to very strong: 9) in which large scale El Niño events occurred (as stated by Quinn, 1992). Middle panel: 11 year moving sum of occurrence (dots) and spline cubic smooth series (line).. Lower panel: 11 year moving average of event's strength (dots) and spline cubic smoothed series (line).

Figure 10 presents the smoothed frequency and average strength curves from Figure 9, together with the transformed GSAT periods and trends from Figure 4. Despite midterm changes, there seems to be some correspondence between the series both in terms of long-term trends and periods. Warming trends grossly correspond to lowered tendencies for El Niño activity (as measured by the decadal frequency and average relative strength), whereas cooling seems to occur during periods of intensification of El Niño activity. Similarly, warm periods tend to occur when El Niño activity is weak, and cold periods when this activity is relatively strong.

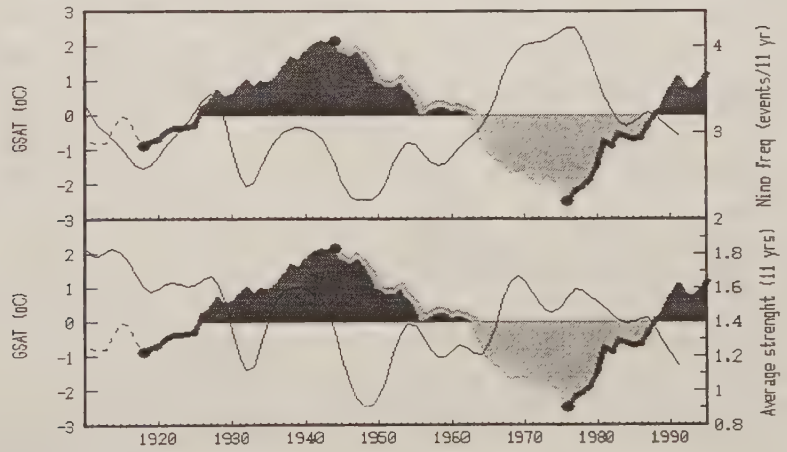


Figure 10. Transformed GSAT series with trends and periods (shade) as compared to the 11 year moving sum of occurrence spline cubic smoothed series (line; upper panel) and 11 year moving average of event's strength and spline cubic smoothed series (line; lower panel).

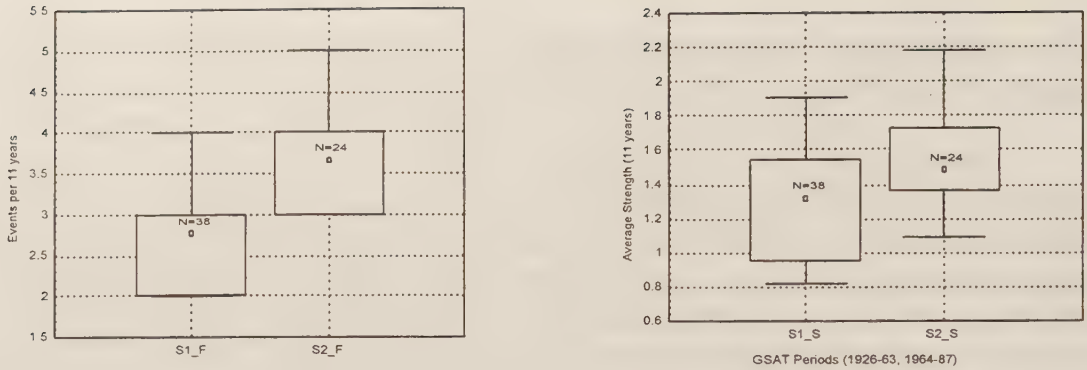
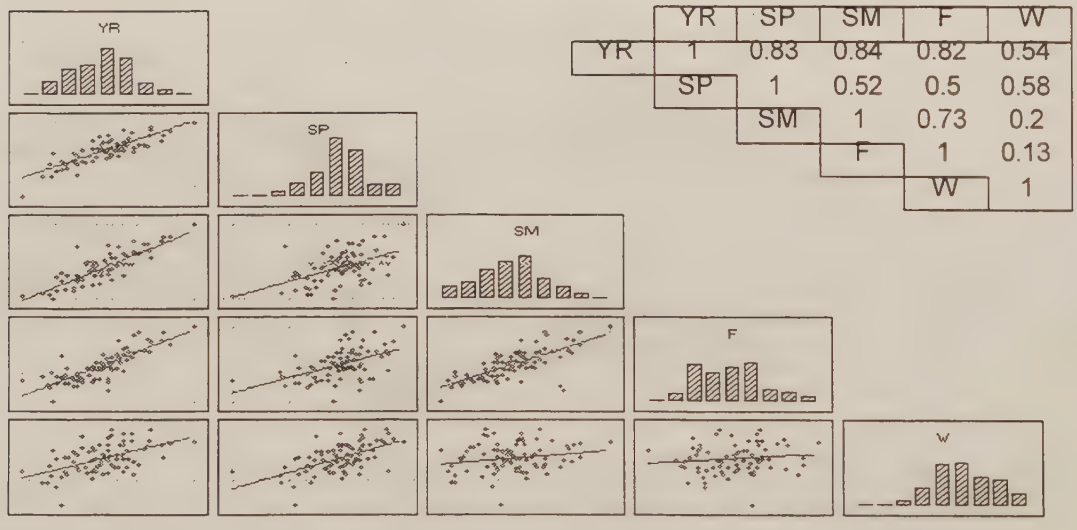


Figure 11. Frequency (upper panel) and strength (lower panel) of 20th Century ENSO events grouped by the two periods (warm: S1 and cold: S2) as defined from the transformed GSAT series.

This general scheme is also evident when looking at the unsmoothed frequency and strength values. Figure 11 shows these data, grouped by the two periods defined from the transformed GSAT series (see Figure 4). The period of positive deviations of 1926 to 1963 had a lower frequency of events (0.25 events/yr) than the period of negative deviations of 1964 to 1991 (0.33 events/yr).

Moreover, about the 75% of the values during the first period were lower than the minimum value observed during the second period. Although less evident, the average strength during the positive period was also slightly lower than that during the negative period (1.3 *vs* 1.5).



	YR	SP	SM	F	W
YR	1	0.83	0.84	0.82	0.54
SP		1	0.52	0.5	0.58
SM			1	0.73	0.2
F				1	0.13
W					1

Figure 12. Correlation coefficients and simple regression lines between SOI yearly (YR) and seasonal mean series (SP: spring; SM: summer; F: fall; W: winter) as computed from monthly values.

However, the Kolmogorov-Smirnov two-way mean comparison (a nonparametric test, since both variables proved to have a non-normal distributions during each period) did not indicate any significant difference between periods, neither in frequency nor in relative strength. Because the variability of both frequency and relative strength is partially influenced by the period selected for computations (11 years), it is possible that significant differences can be found when a different number of years is considered. This is further suggested because weak but significant negative correlations were found between the transformed GSAT series and the unsmoothed frequency series (r^2= -0.64*) for all the 1918 to 1991 period, although relative strength was found not to be significantly correlated (r^2 = -0.28).

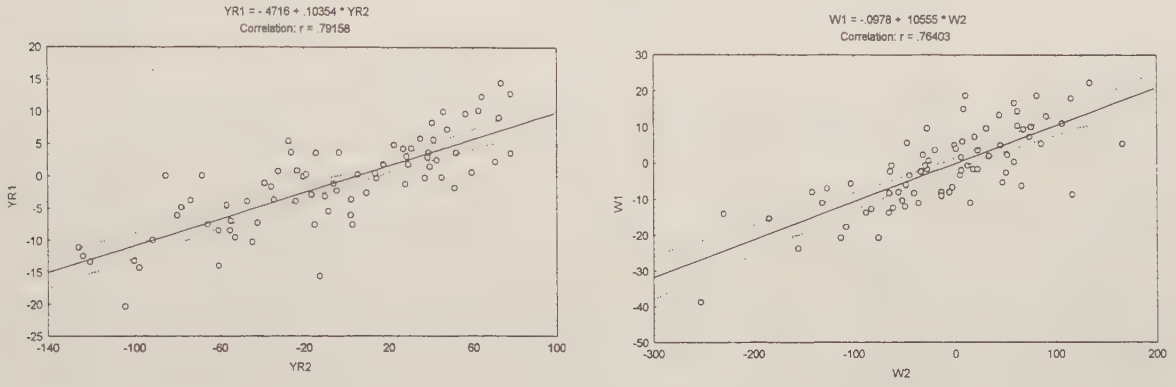


Figure 13. Regression lines of COADS-derived SOI (y-axis) and Tahiti-Darwin SOI (x-axes) for both yearly (left) and winter (right) monthly averages.

3.1.4 Climate regimes as reflected by the SOI index

Figure 14 presents the "composite" yearly and winter SOI series, both the original and the transformed values (*i.e.* 9-term moving average smoothed, detrended, and standardized). The same figure shows, in the lower panel, the two SOI transformed series together with the transformed GSAT as previously presented in Figure 4. This figure suggests opposite trends

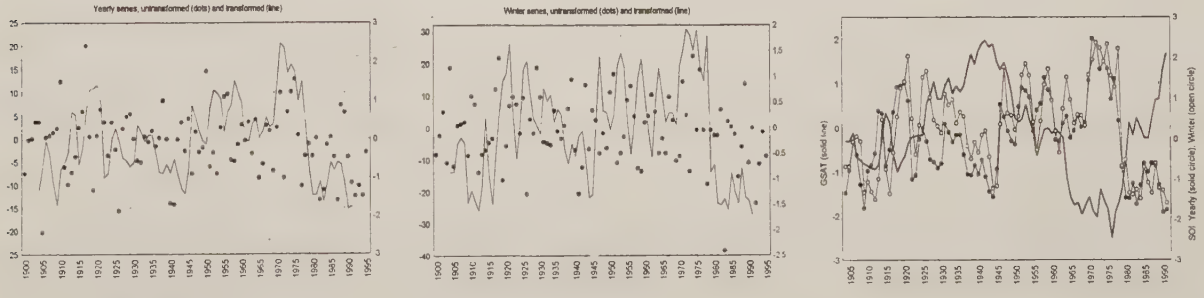


Figure 14. Composite yearly (left panel) and winter (middle panel) SOI series in original (dots) and transformed values (9 yr moving average, detrended and standardized; lines). Right panel: yearly transformed (open circles) and winter transformed (solid circles) SOI series and transformed GSAT series (strong line).

between SOI and GSAT, and thus between SOI and regime trends and periods. This behavior is evident from 1920 on. Actually, negative and statistically significant correlations were observed between transformed GSAT and both transformed SOI series (Figure 15), although the low values of the correlation coefficients indicate these relations are not very close. No major differences were detected regarding the SOI averaged period, although the yearly series proved to be more correlated to the GSAT than the winter series.

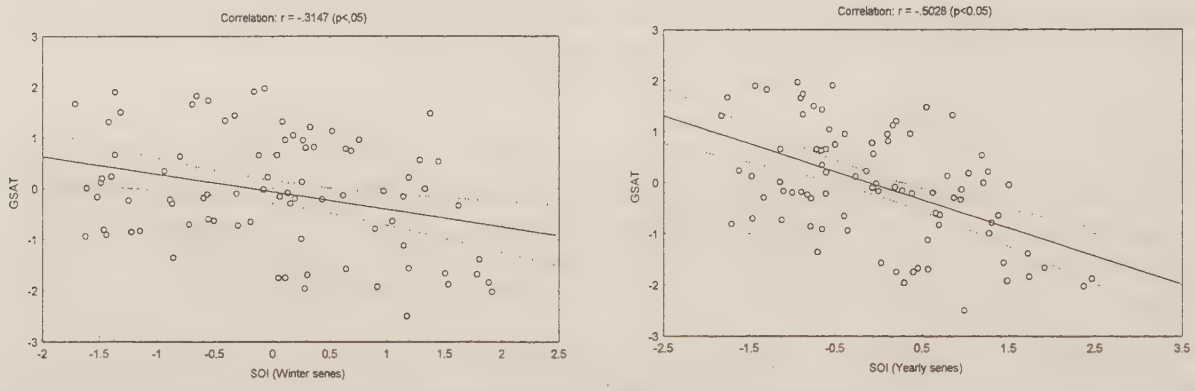


Figure 15. Regression lines between yearly (x-axis; left panel) and winter (x-axis; right panel) SOI series and transformed GSAT series (y-axis).

Observing significant correlations suggests that, during the present century (more clearly since the late 1910s), global warming trends have coincided with decreasing SOI values, whereas increasing values tend to occur during cooling trends. Another possibility to account for a relationship between both variables is that periods of sustained negative SOI values may be globally warm, while during cold periods, positive SOI values could predominate.

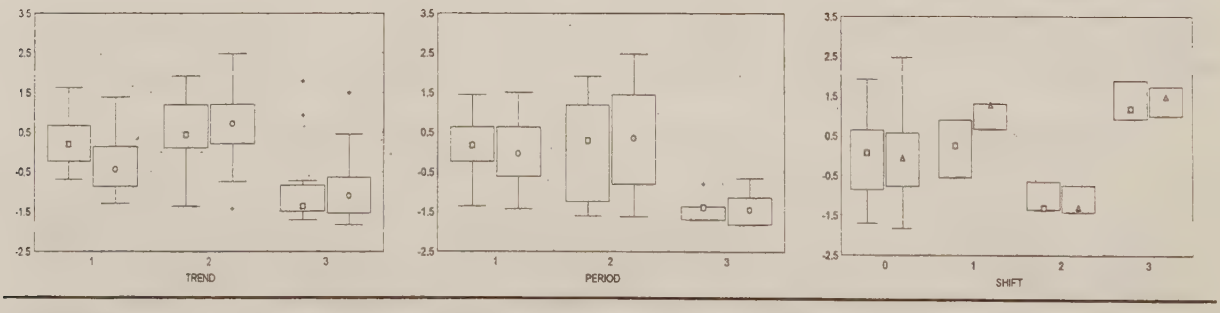


Figure 16. SOI series distributions grouped by trends (left), periods (middle), and shifts (right) as defined from the transformed GSAT. Mean values are indicated by small squares (yearly) and circles (winter). Boxes indicate 25 to 75% percentiles, whiskers indicate extreme nonoutlier values, (+) indicates outlier.

In order to further illustrate this possibility, Figure 16 shows the distributions of transformed SOI series (yearly and winter) grouped by the trends and periods previously detected in the GSAT (see Figure 4). Differences are more or less clear when SOI values, especially those of the winter series, are grouped by trends. Thus, it follows that warming (cooling) trends are broadly coincident to high (low) SOI values. However, it should be noted that this behavior does

not contribute to any possible correlation between GSAT and SOI, because any trend (either warming or cooling) includes almost all the GSAT variability.

Moreover, SOI values do not seem to be different for the periods considered except for the most recent, and this late period includes only a few values. So far we have not explained the observed correlations. Making a closer examination of the SOI series in Figure 14, we note that there are no clear sustained trends, but usually rather sharp shifts from one level to another immediately after a short period with extreme values. For instance, the SOI values during the late 1930s and early 1940s are generally lower that after the late 1940s. Since then, SOI remained relatively high up to the late 1970s, when another strong shift occurred and led to very low values since 1980.

These SOI shifts occur broadly during the same years of regime shifts, but in a different direction. Thus, extreme values of both GSAT and SOI series tend to be simultaneous and opposite. This is probably the reason for the observed negative correlation. The right panel of Figure 16 shows the SOI values grouped according to the regime shift years; 1917 to 19 (group 1), 1943 to 45 (group 2), and 1975 to 77 (group 3). All remaining years were left as group 0. As can be noted, particularly when looking at the winter SOI series, regimen shifts do correspond to extreme values of the SOI index. The two shift periods before a warming trend (groups 1 and 3) were years of high SOI, whereas the shift towards a cooling trend (group 2) had low values of that index. Given this coincidence between regime and SOI shifts, and the negative correlation, the following relationships between regimes and SOI index can be suggested: regime shifts tend to occur when extreme values of the SOI are reached, and regime warming (cooling) trends are characterized as periods of generally low (high) average values of the SOI. In the next section, this possible relation between climate regimes and the SOI is aproached from a different view.

3.1.5 Decadal scale El Niño relative strength and frequency and the SOI

Panels A and B in Figure 17 show El Niño relative strength and frequency as discussed in section 3.1.3. Panel C is the 11-years moving average of the yearly SOI series (open diamonds) and a smoothed curve showing main decadal-scale trends. In panel D we show a series representing the mean SOI condition (positive or negative) in moving periods of 11 years (centered). Horizontal dashed line in this panel represents the 1:1 ratio (0): values below (above) this level indicate more negative than positive (positive than negative) yearly values of the SOI in that 11 year period. Vertical grids in the graph show the changing years between the sustained period of warm and cold anomalies as reflected by the transformed GSAT series (see section 3.1.1).

From the figure, it is to be noted that decadal trends among the SOI average series (panel C) do not match the positive-negative ratio series (panel D), specially for the middle warm period. This is because extreme yearly SOI values, related to El Niño and La Niña years, are masking the more common condition of the tropics in the long term (indicated by the positive-negative ratio). By comparing panels A and B to panel D, it is suggested that, for this time scale, years with positive (negative) values are more frequent than years with negative (positive) values during long-term periods when El Niño events are more (less) frequent and intense.

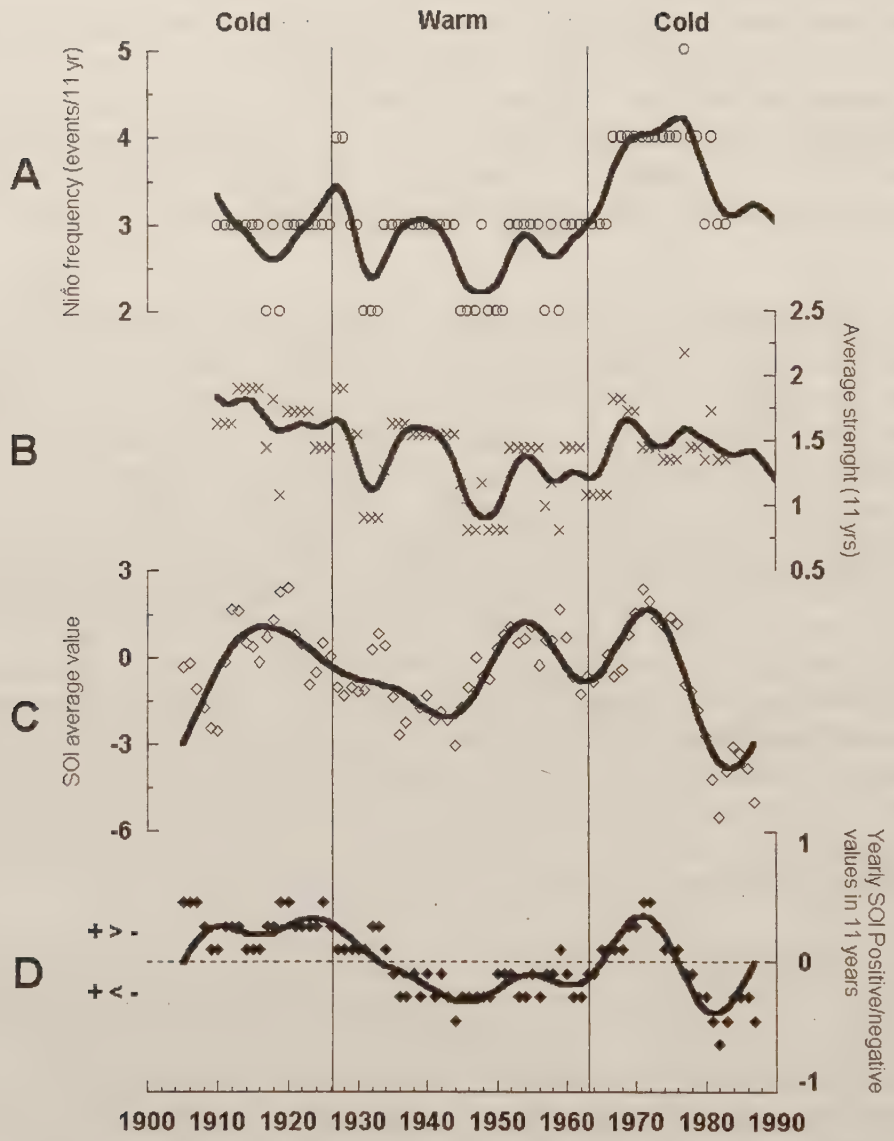


Figure 17. Decadal-scale relative frequency (A) and strength (B) of ENSO events, 11 yr moving average of yearly SOI (C) and 11 yr moving postive-negative ratio of SOI values.

This observation seems to be in contradiction with the normal assumption on negative SOI values being indicative of El Niño activity. However, it should be noted that this assumption is not necessarily correct. While it is true that El Niño events are characterized by largely negative SOI values, it is not true that every negative SOI value is always related to an El Niño. Therefore, it would be possible to have long periods of slightly negative values without any El

Niño occurrence. On the other hand, it would also be possible to have, during a certain long-term period, several and intense El Niño events but still more positive than negative SOI values.

Decadal periods when SOI values are positive (negative) rather than negative (positive) are also periods when the equatorial winds tend to be intensified (diminished). Therefore, it could be suggested that the sea level difference between the eastern and western tropical Pacific is (is not) to grow very large. El Niño is basically a basin-scale adjustment of this sea level difference, generated once the tropical winds are diminished. Therefore, we suggest that this difference may be regarded as the potential for the development of intense and frequent El Niño events. The basic idea would be that long-term periods when this potential is low (trade winds being weak most of the time, SOI being generally negative) will result in few and weak El Niño events, while the opposite would be the case during decadal periods of intense trade winds (SOI being positive most of the time). This idea is further developed after the summary (also see Figure 30).

3.2 Small pelagic regimes

This section is dedicated to the analysis of the regimes of small pelagic abundance. First, these regimes are defined as periods of alternate relative abundances of sardine and anchovies, as inferred from the catch records of the main fisheries worldwide. To facilitate this analysis, a composite series (named regime indicator series, RIS) was constructed based on these catch records. Then, RIS was compared to the global climate regimes as defined in the previous section. Aditional comparisons were made between the RIS and climatic indices reflecting the decade-scale variability of the tropical (*i.e.* ENSO) and extratropical (*i.e.* the Aleutian Low) systems, and also to series of interdecadal variability of solar activity. Similarly, regimes within RIS were used as reference periods when looking for interdecadal climate variations of regions where sardine and anchovy stocks develop.

3.2.1 Definition of small pelagic regimes

Figure 18 shows the RIS values, together with the catch records of each sardine and anchovy stock. From this figure, it seems evident that gross general parallel trends exist; sardines tend to be abundant worldwide when anchovies are at low population levels, and *vice-versa*. Despite these general trends, it is also evident that values and trends within the catch records of the various stocks do differ from one another, particularly when year-to-year changes are considered. Catch records are only a gross index of large abundance changes, moreover, variations are a function of global climatic factors linking the different areas, and also of particular effects that would tend to differ between regions. Therefore, neither the composite RIS nor any particular catch record should be expected to closely reflect the effects of interdecade climate variability of small pelagic populations.

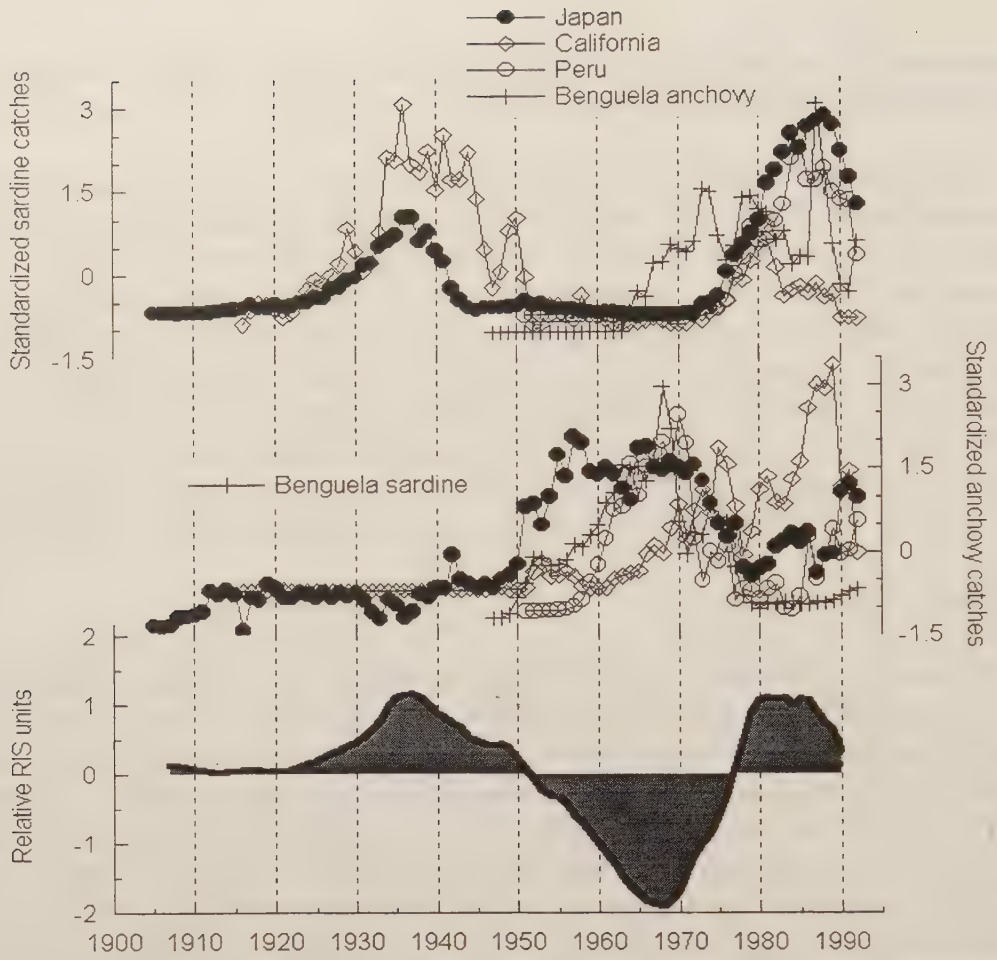


Figure 18. Upper pane: Standardized catches off Japan, California, and Peru sardine and Benguela anchovy (upper panel); and Japan, California, and Peru anchovy and Benguela sardine (middle panel). Lower panel: Regime Indicator Series (RIS) as computed from all catch records.

Despite the limitations, we believe the RIS is a better indicator of decadal trends than any individual record, because any composite series would tend to emphasize the common long-term variability while reducing the effects of the individual year-to-year variations. Using standardized values when computing the RIS values tends to compensate for those stocks that reached very high abundances, such as the Humboldt anchovy and the Japanese sardine, as compared to those stocks of less productive systems as California.

Since more direct estimations of stock abundance have not been made for all the areas and for periods long enough as to reflect the interdecadal regime variations, the RIS (or any similar composite series based on catches) might be the only available data for assessing the effects of climate variability on pelagic resources on a worldwide basis. This type of evidence is considered useful for the study of interdecadal climate variability, given the lack of both a more complete knowledge of the physical mechanisms and of long records for some physical variables in poorly studied areas (Sharp and McLain 1992).

Figure 18 shows there is no clear tendency during the first years of the RIS series, a period when most fisheries were at their beginning. Therefore, catch of those years cannot be

expected to reflect large abundance changes because of the low level of effort. After this period, sardines were abundant worldwide from 1925 to 1950, peaking around the mid-1930s. Thereafter, anchovies dominated from the early 1950s up to the late 1970s, peaking around the late 1960s. The late 1970s and most of the 1980s were again years of sardine abundance, but recently (early 1990s) the sardine dominance has been declining (remembering the Benguela stocks fluctuate "out of phase" with the others, see Lluch-Belda *et al.* (1989, 1992). Special considerations were used regarding these stocks when computing the RIS series. See data and methods section.)

We note, except for the first years of the RIS series, there has been no prolonged period when both sardines and anchovies show similar population levels, that is, the RIS values are either positive or negative but no near-zero values are observed for more than one consecutive year. Moreover, the alternation between sardines and anchovies stocks is an interdecadal variation, as previously noted by Kawasaki and Omori (1988) and Lluch-Belda *et al.* (1989, 1992).

3.2.2 Small pelagic regimes and global climate regimes

Figure 19 presents the RIS series as compared to the transformed GSAT from Figure 4. Parallel trends between global climate regimes (as reflected within the GSAT) and small pelagic regimes are very evident for most of the series length. It is also evident that population changes of small pelagics tend to anticipate the interdecadal variations of the global climate. The same Figure 19 presents the cross-correlations for both series, correlation coefficients are significant for most lags, but the highest are observed when the RIS lags 7 to 9 years. This result suggests that the regime variations are to be reflected first as large population changes among small pelagic stocks, and only some years later as a global climate signal. The reasons for this result are not clear at this point.

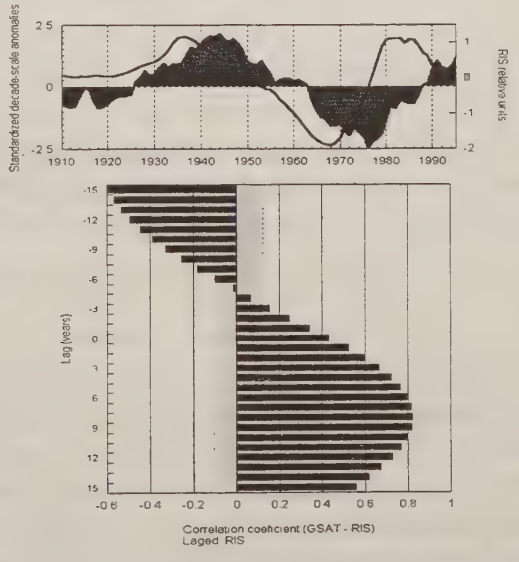


Figure 19. Upper panel: Transformed GSAT (shaded) and RIS (solid line) time series. Lower panel: Cross-correlation coefficients between transformed GSAT and lagging RIS (bars). Correlation coefficients are significant out of the standard error area (shaded).

Therefore, we are intrigued by the question of weather the global interdecadal variability observed within the GSAT could be somehow be linked to much earlier environmental changes at the boundary systems of the oceans where small pelagic stock develop. This possibility seems interesting and, if confirmed, might provide a way to "anticipate" by several years the direction of the interdecadal changes in the global climate. Regarding this, a new trend of the RIS series is on its way since the mid 1980s, towards the end of the recent sardine abundance regime and probably the beginning of a new worldwide anchovy abundance regime as experienced during the 1950s to 1970s. If the RIS-GSAT lagged-relationship holds true, small pelagic recent changes would also suggest a new global cooling trend may be starting around the mid 1990s. While it may be too soon for claiming such a trend to actually exist, that some global air temperature records (particularly for the northern hemisphere) peaked during the early 1990s but decreased thereafter is, at least, very suggestive (Figure 20, also see Figure E3 in any recent issue of the monthly NOAA/NPC Climate Diagnostic Bulletin).

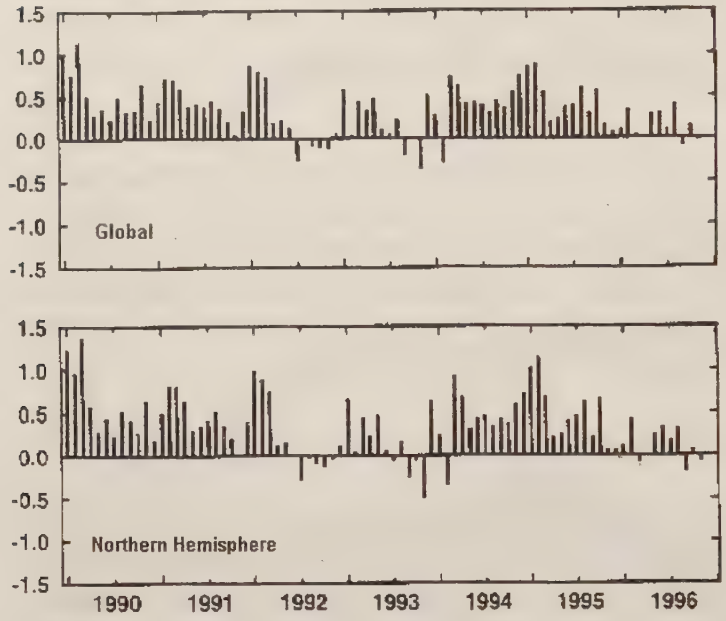


Figure 20. Monthly global (upper panel) and Northern hemisphere (lower panel) surface temperature anomalies (land only, °C) as published at the November 1996 Climate Diagnostics Bulletin (CCP-NOAA-NWS-NCEP).

3.2.3 Small pelagic regimes and tropical-extratropical interdecadal variability

In previous sections (see 3.1.3 to 3.1.5), the connection between ENSO variability and global climate regimes was explored. The results suggested some relationship between both is detectable but not very close. Therefore, we consider that other influences, besides the tropical variability, are also important when looking for the regime signals, both climatic and among small pelagic populations.

However, extratropical systems are not as well studied as ENSO variations, thus information on their relative importance for determining global variability is scarce in most cases. One exception is the Aleutian Low Pressure System, a dominant meteorological feature in the winter and spring North Pacific atmosphere that has strong links to North Pacific oceanography (Namias 1969). Figure 21 shows the smoothed Aleutian Low normalized sea level pressure (AL), together with the smoothed SOI series. Viewing their interdecadal variability, it seems evident both systems show parallel trends for most of the time, the exceptions being two periods during the late 1920s and early 1970s. These periods of unrelated behavior are more evident when looking at the absolute differences between both indices, in the bottom panel of Figure 21.

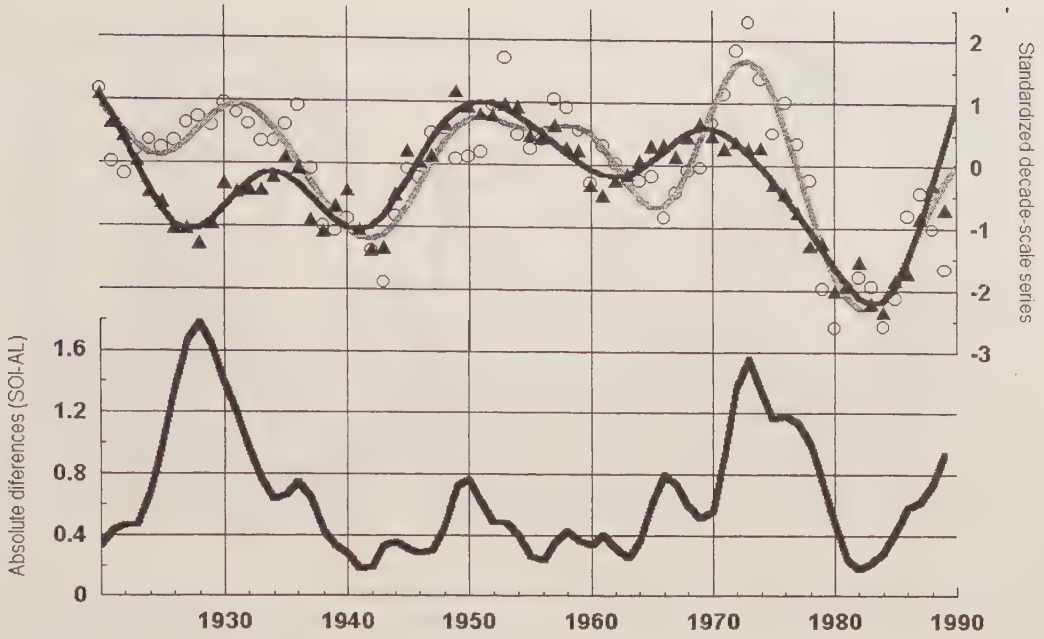


Figure 21. Upper panel: Transformed (standardize/11-year moving average smoothed) series of SOI and AL indices. Lower panel: Absolute differences between transformed SOI and AL series.

As mentioned at the introductory section, the origin of decadal-scale variability has been attributed to both the tropical and the extratropical systems by different authors, and to date no definitive conclusions have been reached. The controversy can be summarized as follows: whereas the identification of decadal signals in ENSO indices is considered by some (Graham 1994, Jacobs *et al.* 1994, Zhang *et al.* 1996) as strong evidence supporting the idea of a tropical forcing, some modeling results suggest that realistic simulations of extratropical variability of the North Pacific can be generated even without any input from the tropical Pacific system (Latif and Barnet 1994, 1996; White and Cayan 1996). If tropical forcing is to be considered the main source of extratropical variability, we would expect a parallel behavior of the series shown in Figure 21; these parallel trends do seem to occur generally but not all the time. Therefore, we believe the SOI-AL relationship is significant because it suggests the tropical forcing of the extratropics is not a constant mechanism.

Figure 22 shows the series of absolute differences between the SOI-AL indices together with the transformed sunspot numbers series. Results strongly suggest an inverse relationship between the two series, with the observed negative correlation coefficient (-0.5) being statistically significant. Therefore, large (small) SOI-AL absolute differences seem to occur during periods of low (high) solar activity. Assuming the degree of coupling of the tropical and extratropical systems could be reflected by a gross index such as the SOI-AL series, our results would suggest that those periods of relatively high solar activity tend to promote this coupling and therefore result in small SOI-AL differences. Somewhat independent tropical-extratropical variability (and therefore large SOI-AL differences) would tend to occur during periods of moderate to low solar activity. However, the effects of solar variability on the climate system of the earth are still a matter of controversy.

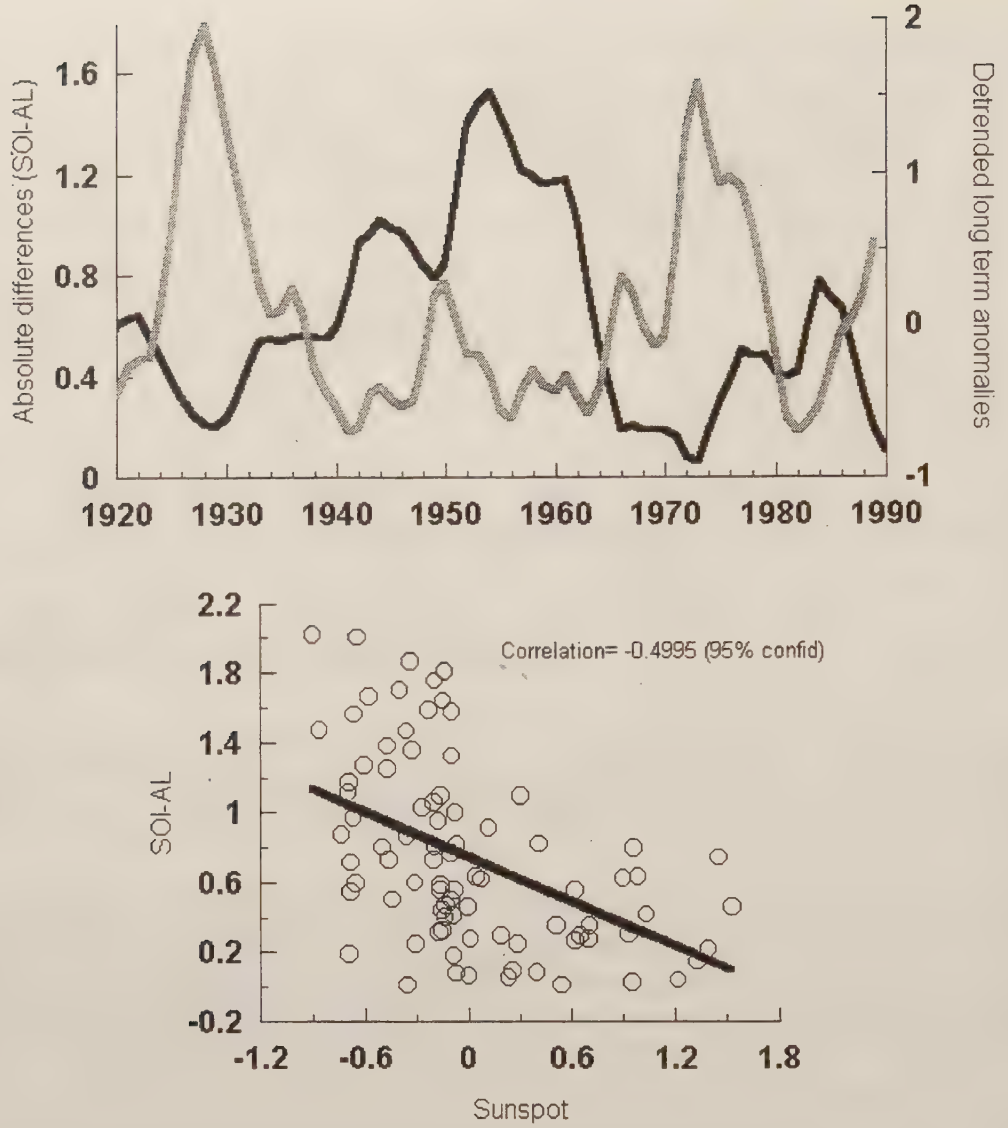


Figure 22. Upper panel: Absolute SOI-AL differences (lighter line) and detrended 11 year moving average anomalies of number of sun spots (area; data from the Sunspot Index Data Center-Royal Observatory of Belgium). Lower panel: Regression line and correlation coefficient between transformed Sunspots signal (x-axis) and absolute SOI-AL differences (y-axis).

Figure 23 shows the SOI-AL series as compared to the RIS regimes, These latter are identified by regression lines showing the general trends during selected periods. Periods when the SOI-AL differences are large tend to be of sardine (anchovy) population growth (decline), while anchovy (sardine) growth (decline) periods tend to occur when the SOI-AL differences are small. From the previously suggested relationships, it would follow that sardine growing periods (upward RIS trends) would tend to occur during years of diminished solar activity, when the tropical and the extratropical systems tend to behave independently. Anchovy growing periods (downward RIS trends) would take place during periods of increased solar activity and coupled tropical-extratropical interdecadal variability.

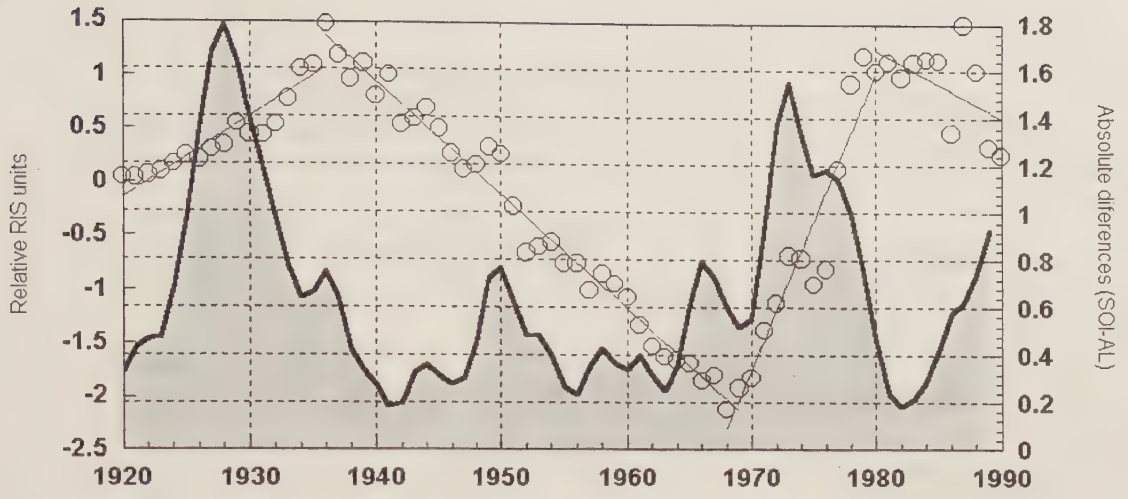


Figure 23. Absolute SOI-AL differences (shaded area) and RIS (open circles) with trends evident by the partial linear regressions (fine lines).

3.2.4 Small pelagic regimes and regional interdecadal climate variability

Periods of low (1941 to 1961) and high (1971 to 1977) differences of the SOI-AL series were used as reference periods for computing departures from the seasonal cycle of sea surface temperature (SST), sea level pressure gradient, and thermocline depth within selected systems (Figure 2). Figures 24 and 25 present the results of the analysis for the SST variability, Figures 26 and 27 those of pressure gradient, and Figures 28 and 29 those of thermocline depth.

SST results for most systems where large populations of sardines and anchovies grow suggest that periods of large SOI-AL differences (1971 to 1977) tend to be warmer than those periods when the tropical and the extratropical indices show parallel trends (1941 to 1961, when the SOI-AL differences are relatively small). California, Japan, Humboldt, and the Canary systems seem to behave this way. The only exception is the Benguela system where no difference between periods seems particularly evident. A similar tendency is also noticeable for the Eastern Tropical Pacific, whereas other systems such as Australia, Brazil, and Somali tend to behave in the opposite way.

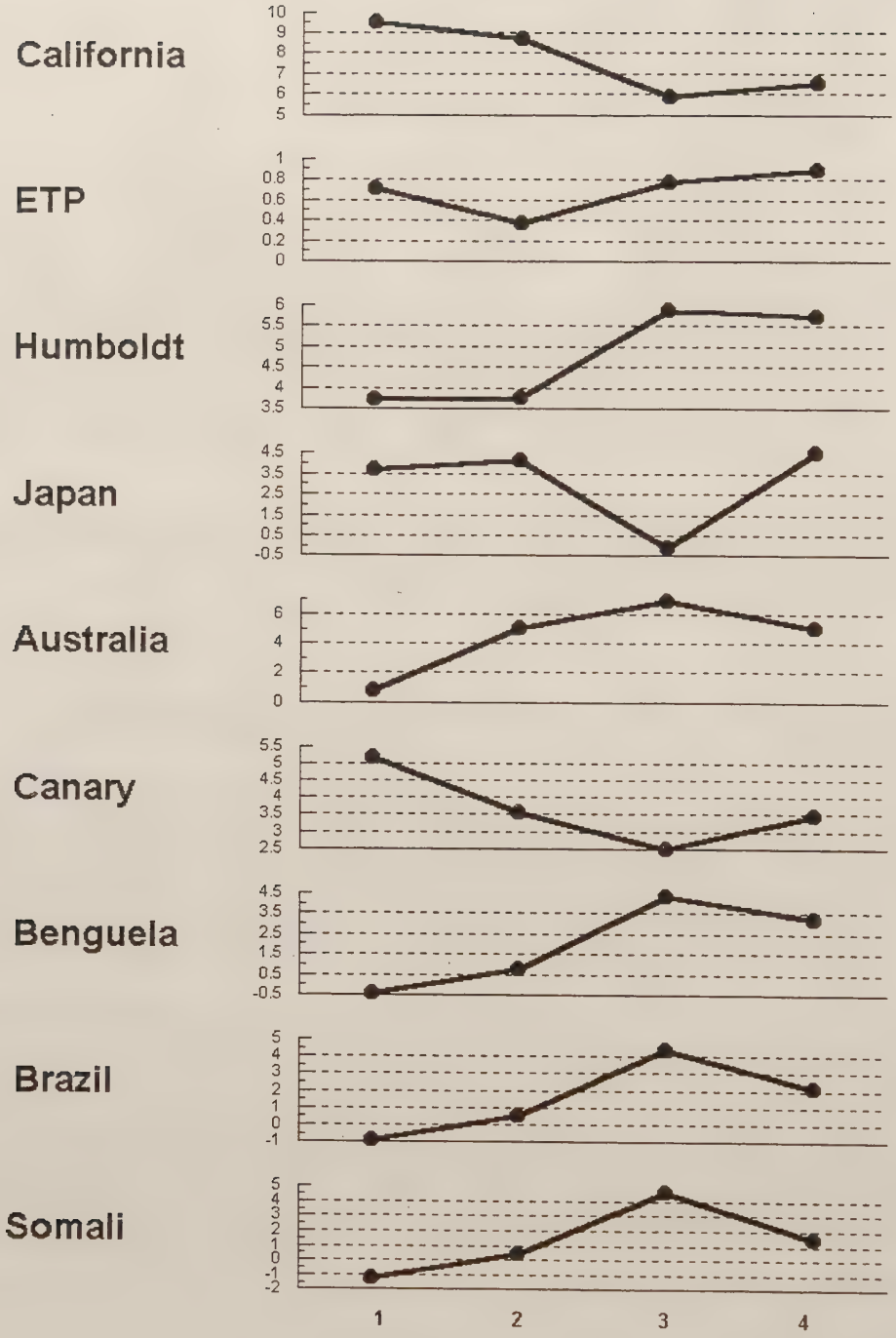


Figure 24. Seasonal climatology (1: winter, 2: spring, 3: summer, 4: fall) of SST for the nine boxes shown on Figure 2. Base period: 1900 to 1990.

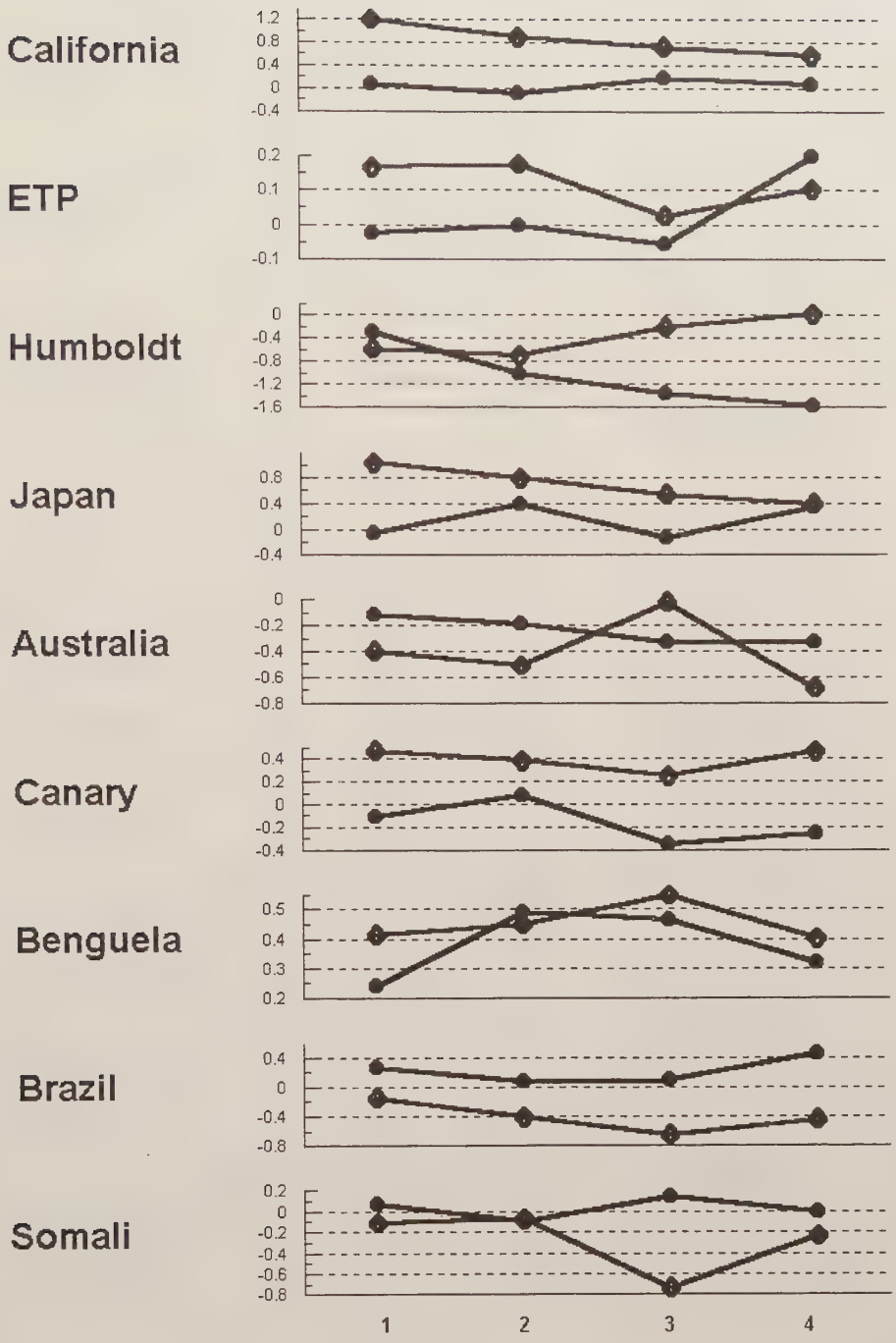


Figure 25. Seasonal departures (1: winter, 2: spring, 3: summer, 4: fall) of SST for the nine boxes shown in Figure 2. Referenced periods : 1941 to 1961 (solid circles) and 1971 to 1976 (open diamonds).

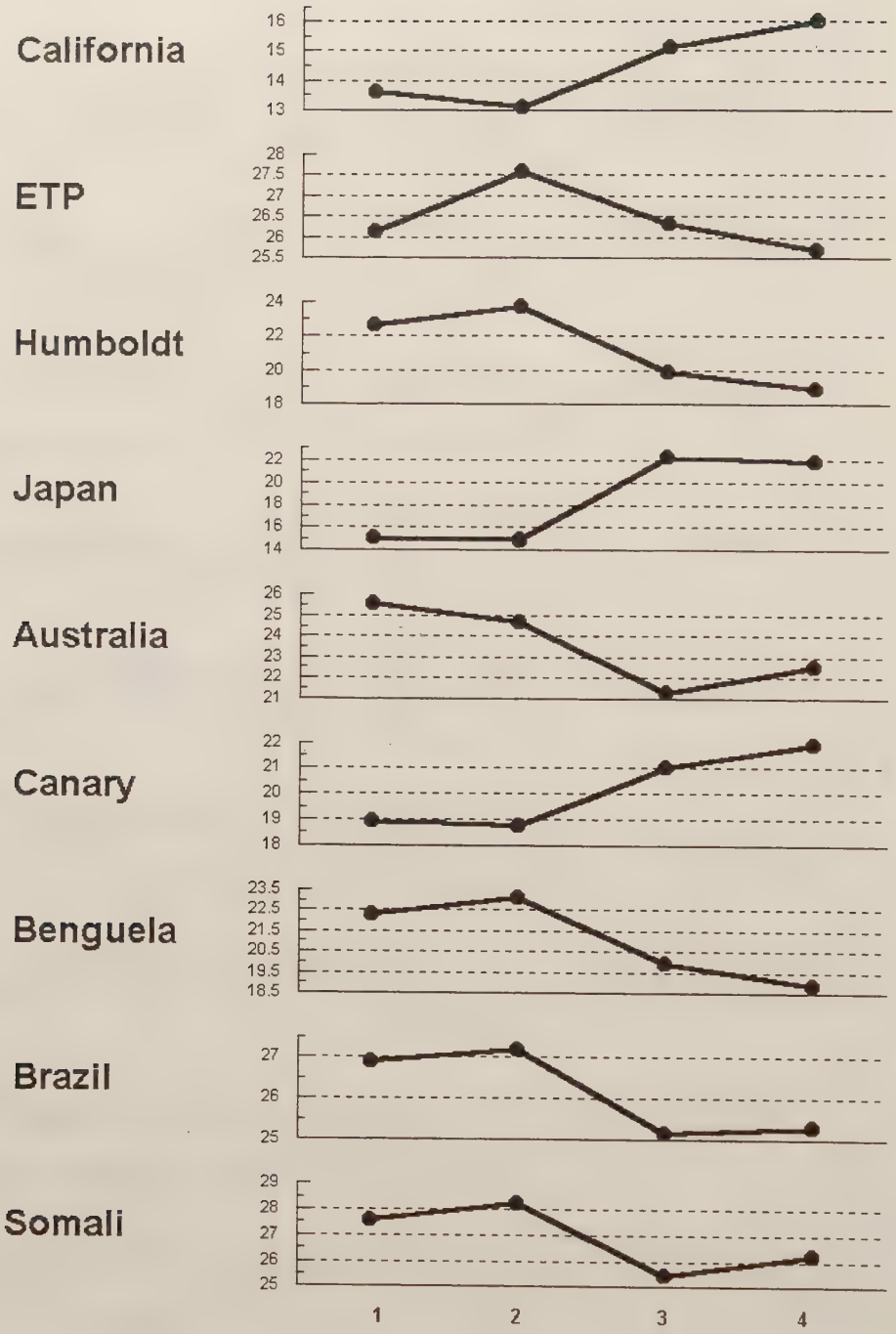


Figure 26. Seasonal climatology (1: winter, 2: spring, 3: summer, 4: fall) of SLP indices for the nine boxes shown in Figure 2. Base period: 1900 to 1990.

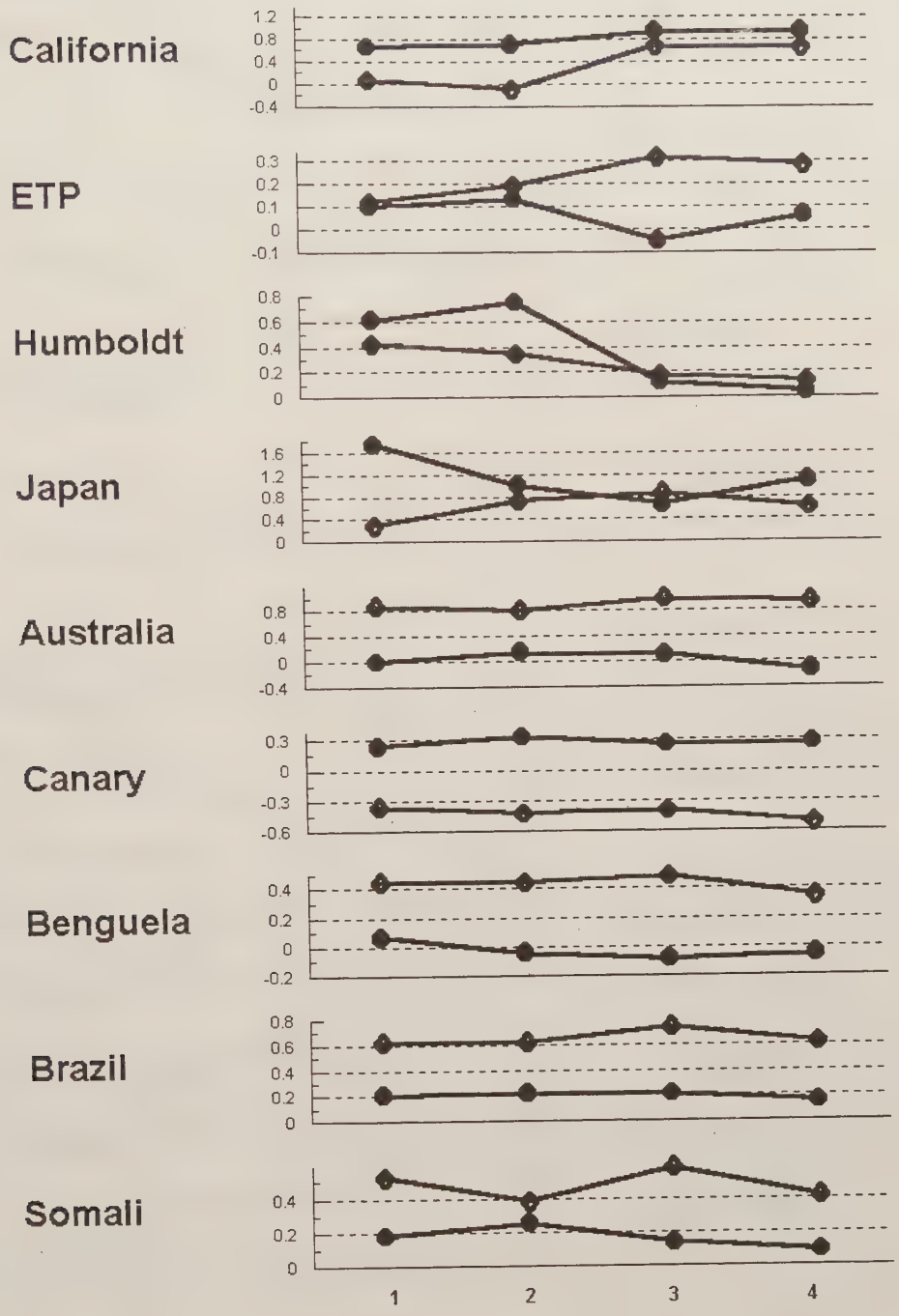


Figure 27. Seasonal departures (1: winter, 2: spring, 3: summer, 4: fall) of SLP indices for the nine boxes shown in Figure 2. Referenced periods : 1941 to 1961 (solid circles) and 1971 to 1976 (open diamonds).

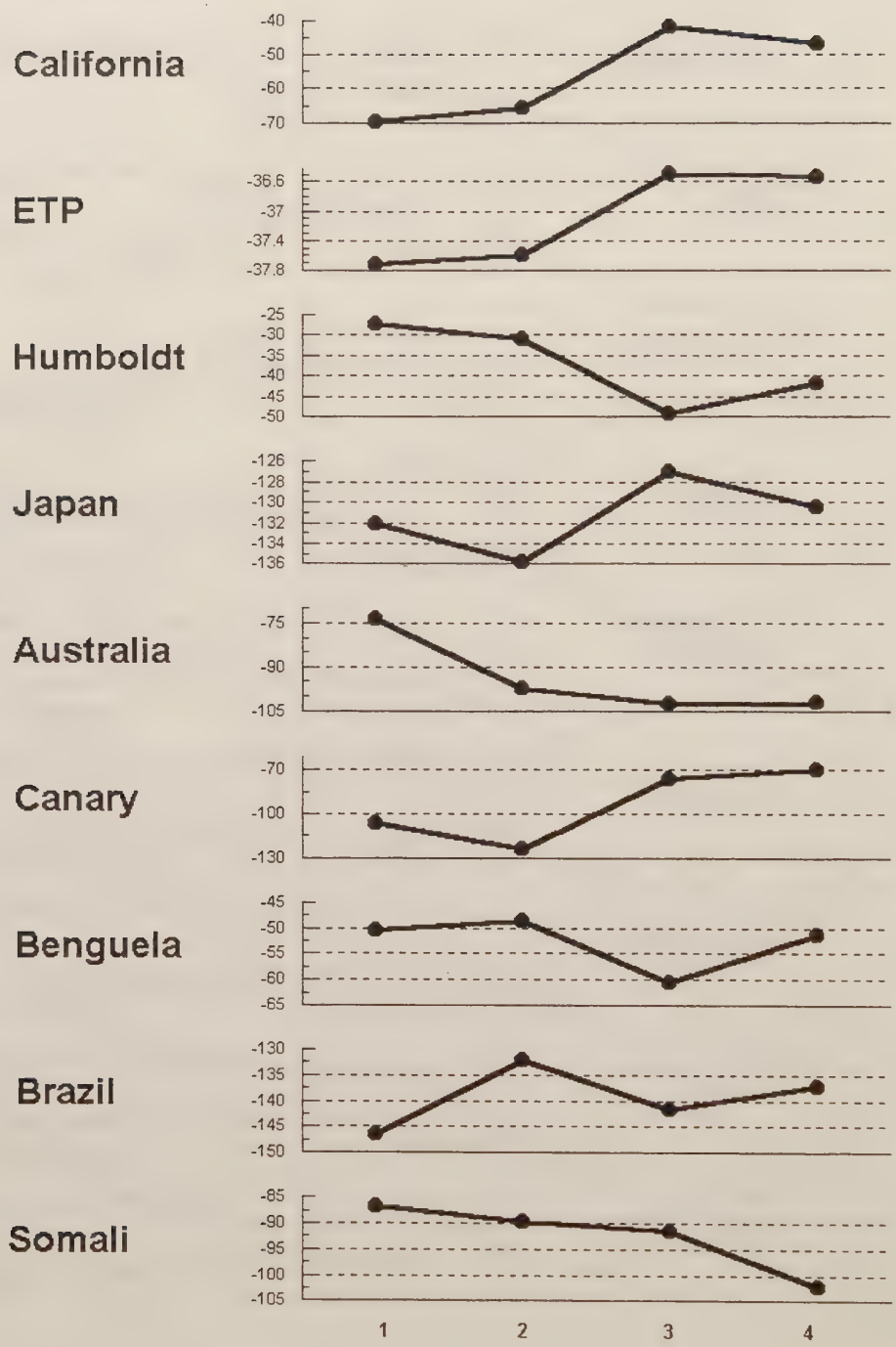


Figure 28. Seasonal climatology (1: winter, 2: spring, 3: summer, 4: fall) of thermocline depth for the nine boxes shown on Figure 2. Base period: 1900 to 1990.

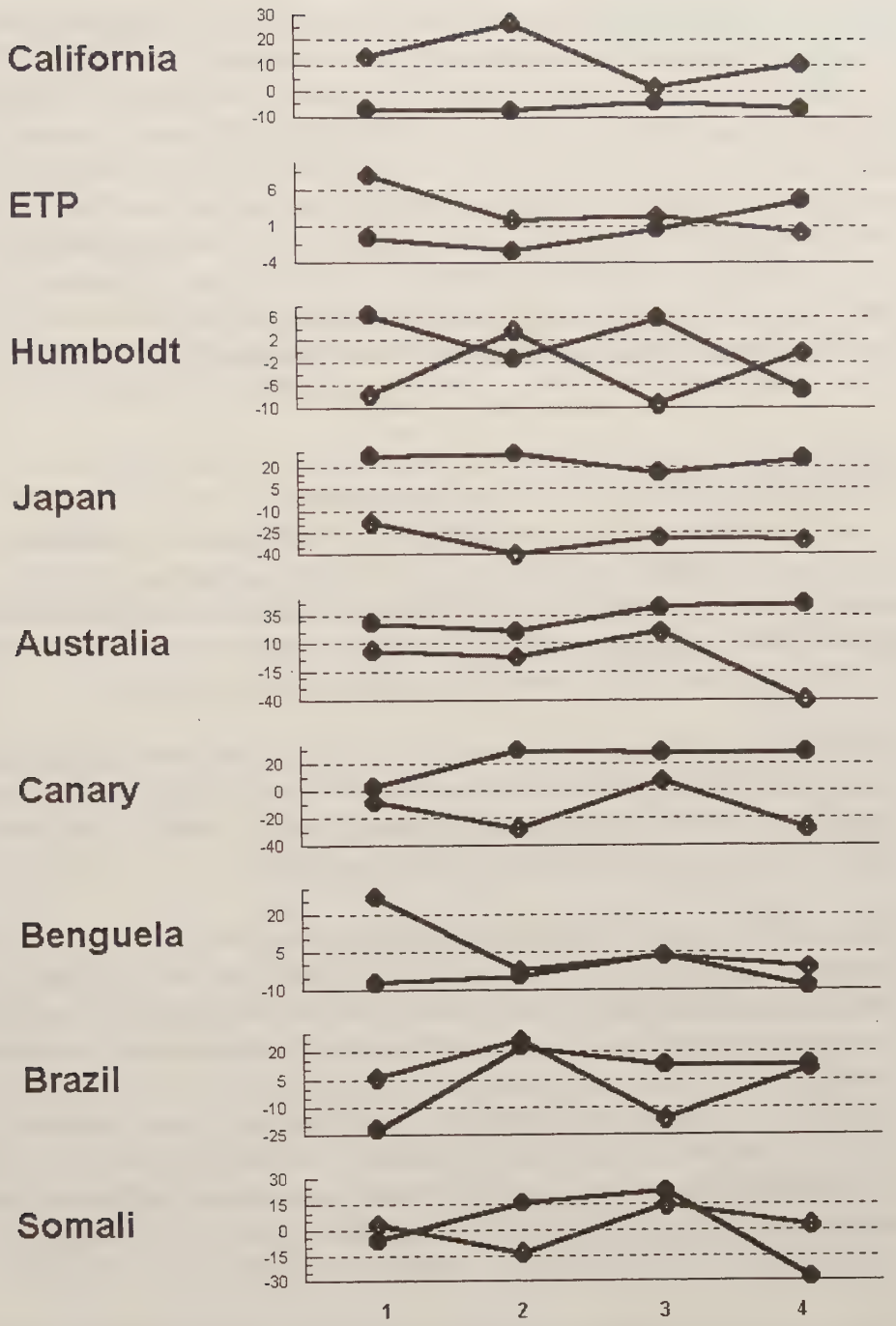


Figure 29. Seasonal departures (1: winter, 2: spring, 3: summer, 4: fall) of thermocline depth for the nine boxes shown in Figure 2. Referenced periods : 1941 to 1961 (solid circles) and 1971 to 1976 (open diamonds).

However, the described pattern is not evident from the thermocline depth analysis. Whereas this feature tended to be shallow in California and the Eastern Tropical Pacific during the 1971 to 1977 period, it tended to be deeper in Japan and Canary, and no clear tendencies are evident for the other systems where large fisheries of small pelagics occur (Humboldt and Benguela). At this point, it is not clear whether this lack of a coherent pattern is the result of the particular dynamics of each system or an artifact related to data scarcity. Similar ambiguous results were obtained for the pressure gradient analysis. Despite that differences for most systems seem to occurr between the selected periods, no coherent pattern is observed. It is evident that proper evaluation of the interdecadal variability at the regional level will require more detailed approaches than the general analysis intended within this work.

4. SUMMARY

Up to this point, we believe the analyses have yielded some preliminary but interesting results. While some findings do not seem to have a simple explanation at this point, others may allow us to draw some preliminary hypotheses of the possible relationships linking climate regimes, small pelagic regimes, and ENSO activity. Before attempting to do so, however, it would be useful to summarize the results and conclusions obtained so far:

- The GSAT seems to be a sensible index of the variability of the climate regimes; in other words, *the regime signal seems evident when looking at this global climate index*. Within this series, and for most of the present century, regimes are evident as sustained (cooling and warming) trends and (cold and warm) periods.

- Except for the most recent, this century's *climate regime trends and periods lasted for several decades* (more than two and less than four). The 1870 to 1915 period seems to behave in a different way on the interdecadal time scale: trends and periods are *shorter*, and do not account for as much variability as the regimes of the present century.

- As reflected by the GSAT, *global climate regimes grossly correspond to regimes of small pelagic abundance* as previously described by Lluch-Belda *et al.* (1989). Thus, regime changes are to be considered as a *global phenomena linking climate variability of distant areas*, and having wide and *similar* effects on (at least some of) the biological components of oceanic systems.

- Despite being global phenomena, even a gross examination indicates that *climate regimes are not homogeneous at different latitudes*. As reflected by the GSAT series, regimes are strong and directly related to the air temperature over large areas at the northern and equatorial latitudes. There, climate regimes may account for as much as 80% of the regional variability on the interdecade time scale. However, at southern latitudes the regime signal becomes weak; and there are some indications of a weak and inverse relation between the GSAT and the southernmost areas.

- Although not a close one, there seems to be an *inverse relationship between the frequency of El Niño events and the climate regimes*. Warming (cooling) trends grossly correspond to periods of few (many) events, El Niño may be 2.5 times more frequent during cooling

than during warming periods. Similarly, the so-called relative strength of the events (as stated by Quinn 1992) seems to be inversely related to the climate regimes: warming trends grossly correspond to periods of events weaker than those occurring during cooling periods.

- For the SOI index, *climate regime shifts tend to occur when extreme SOI values are reached;* highly positive (negative) values have been observed at the onset of warming (cooling) trends.

- *Warming (cooling) trends of climate regimes may be characterized as periods of generally low (high) average values of the SOI.*

- *In time-scales longer than the interannual, extreme SOI values (El Niño and La Niña events) could mask the more common condition of the tropical Pacific as reflected by the positive-negative SOI values rate.*

- *At a decadal time-scale, positive (negative) SOI values tend to be more frequent than negative (positive) years in periods when ENSO events are more (less) frequent and intense.*

- Despite its limitations, *the RIS seems to be a good indicator of the small pelagic regimes;* at least a better one than any individual catch record because this composite series tends to emphasize the common long-term variability while reducing the effects of the individual year-to-year variations.

- As reflected by the RIS, sardines were abundant worldwide from 1925 to 1950, peaking around the mid-1930s. Thereafter, anchovies dominated from the early 1950s up to the late 1970s, peaking around the late 1960s. The late 1970s and most of the 1980s were again years of sardine abundance, but recently (early 1990s) the sardine dominance has been declining. When considered globally, *it seems evident that the alternation between sardine and anchovy stocks is basically an interdecadal signal.*

- If the RIS-GSAT lagged-relationship holds true, *recent trends of small pelagics suggest that both a period of worldwide anchovy abundance and a global cooling trend may be on their way*, starting around the mid 1990s.

- For the relationship between the ENSO, as a tropical mechanism, and the Aleutian Low, as a component of the extratropical climate system, our results suggest that those *periods of relatively high solar activity tend to promote tropical-extra tropical coupling.* Somewhat independent tropical-extratropical variability tends to occur during periods of moderate to low solar activity.

- For the global regimes of small pelagics, *sardine growing periods (upward RIS trends) seem to occur during years of diminished solar activity, when the tropical and the extratropical systems tend to behave independently.* Anchovy growing periods (downward RIS trends) would take place during periods of increased solar activity and

coupled tropical-extratropical interdecadal variability.

- At the regional level, the SST of most systems where large populations of sardines and anchovies grow suggest that periods of (1) diminished solar activity, (2) large SOI-AI differences, and (3) sardine population growth tend to be warmer than those periods when the opposite conditions are observed. However, no such a globally coherent picture was observed for thermocline depth or pressure gradient.

Some of these observations and preliminary results can be included in an hypothetical mechanism linking ENSO and regimes, which is schematically presented in Figure 30. In this figure, we propose two basic "modes" or "stages" for the tropical Pacific ocean-atmosphere system: a "weak circulation" stage characterized by relatively low values of the SOI index, and a "strong circulation" stage characterized by relatively high values. Each of these modes would correspond to high and low levels of interdecadal solar activity; increased (diminished) activity would promote an intensification (relaxation) of the atmospheric circulation, probably because of stronger (weaker) pressure gradients. From the observed relationship between solar activity and the SOI-AL series, we suggest the coupling of the tropical-extratropical systems is probably forced by high solar activity and the resulting strong circulation mode, whereas weak circulation resulting from comparatively low solar input would promote a decoupling of the tropics and the extratropics.

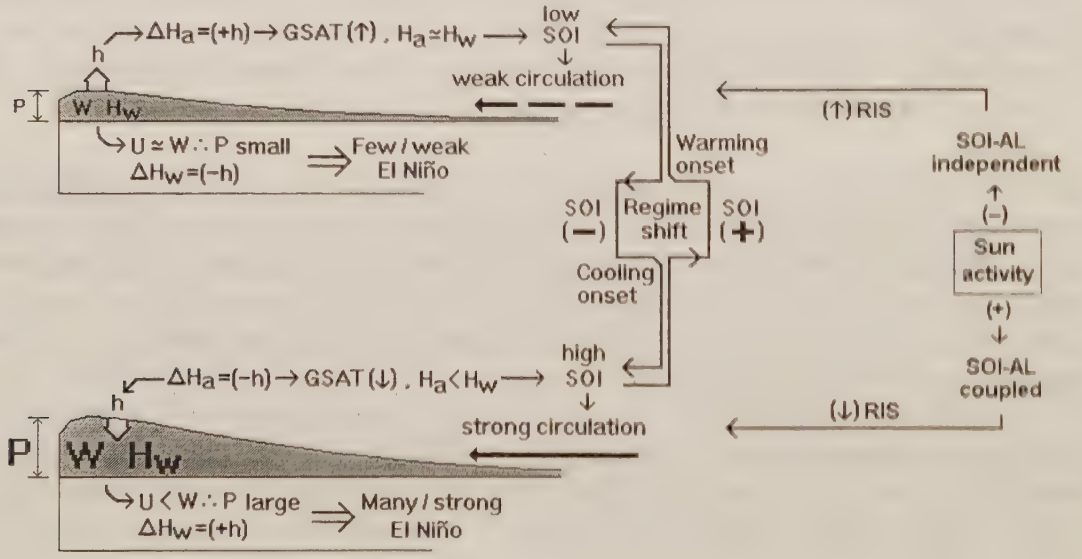


Figure 30. Schematic representation of the hypothetical mechanism linking ENSO and Regimes

In the "weak circulation" mode (upper panel), trade winds over the tropical Pacific would tend to be generally weak, in response to a comparatively small pressure difference between eastern and western areas. Thus, SOI index is to remain relatively low. If trade winds are weak, the sea level difference between western and eastern Tropical Pacific can not become too large.

Though trade winds tend to pile surface water towards the west, some of this water is redistributed by surface poleward currents (not shown) and the equatorial undercurrent systems (indicated as U). Thus, the sea level difference (P) caused by the weak trade winds may be partially overcome. This difference in sea level, we propose, may be regarded as the "potential" for an El Niño events, in the sense that it must be large for a strong El Niño to develop. The idea is that, at low values of P, any sudden shift of the Southerns Oscillation (SO) will probably not result in the onset of an El Niño event, or at most, the event will rank from weak to moderate.

The hypothesis contemplates another feature that may inhibit the onset of strong events during the "weak circulation" phase. Because the results show that during these periods the GSAT undergoes a warming trend, some heat transfer from the tropical ocean to the atmosphere may be involved. Some authors (e.g. Jones and Wigley 1990) mentioned that, regarding the GSAT, El Niño events are to be considered as cold events because a net heat transfer occurs from the atmosphere to the tropical ocean, thus cooling the air. La Niña episodes are considered by Jones and Wigley (1990) as leading to years of high GSAT, because these events imply a heat transfer in the opposite direction.

Therefore, during a "weak circulation" phase El Niño events are probably weak and relatively infrequent; and their cooling effect on the atmosphere may also be weak and infrequent. Let us suppose that in "average" conditions (*i.e.* when no tropical event occurs, neither Niño or Niña) there is a net heat transfer from the tropical ocean to the atmosphere. If so, the cooling of the air produced by only a few and weak El Niños may not overcome the air "average" heating. Thus, in the long run, the air may gain heat ($\Delta Ha = +h$) as it is released from the tropical ocean ($\Delta Hw = -h$), therefore explaining the upward trend of the GSAT. Moreover, this warming of the air may result in a weak ocean-atmosphere heat gradient ($Ha \approx Hw$), which in turn may reinforce the "weak circulation" phase. In other words, the proposed mechanism implies a positive feedback, not to be overcome unless a major shift of the SO forces the system to the alternative "strong circulation" phase.

The rationale for the other phase is similar to that previously stated. Now trade winds are generally strong, as indicated by the comparatively high values of the SOI index. More water is now piled into the western Pacific, and the influx is not overcome by the surface poleward currents and the equatorial undercurrent ($U<W$). This results in an increased slope of the sea level, thus in a larger "potential" (P) for El Niño events. Under these conditions, any sudden shift of the SO will probably result in the onset of an El Niño event, ranking from moderate to strong. Since more and stronger El Niños are supposed to occur during this phase, frequent and intense cooling of the atmosphere may result. This effect may totally overcome the "normal" direction of the heat flux (from the tropical ocean to the atmosphere) and result in a net heat transfer from the air ($\Delta Ha = -h$) to the tropical ocean ($\Delta Hw = +h$) and therefore in a downward trend of the GSAT. As the global air temperature drops, the ocean-atmosphere heat gradient increases ($Ha < Hw$); a positive feedback of the "strong circulation" phase. Again, this feedback is not

overcome until a major shift of the SO forces the system towards the alternative "weak circulation" phase.

Since each phase is characterized by a sustained trend within the GSAT, the transition from one phase to the other implies a shift in the climate regime. As previously observed, shifts in the climate regime have occurred at extreme values of the SOI index. The onset of a warming trend follows extreme positive values, while strongly negative SOI have preceded the onset of a cooling trend (see Fig. 15). Extending the proposed scheme, we suggest that the changes in the tropical ocean-atmosphere heat transfer that may occur at both extremes of the SO may explain the change from one phase to the other.

According to this idea, the "weak circulation" feed back, reinforced by the small heat gradient which results from the tropical ocean to atmosphere net heat transfer, may end if a strong El Niño develops. Such an event would imply the heating of the water as well as the cooling of the air, therefore, the heat gradient would increase. When the gradient becomes large enough, strong circulation may result, and this in turn would tend to maintain the high gradient. A "strong circulation" phase may end if a strong La Niña event develops, since such an event would result in a weakening of the ocean atmosphere heat gradient caused by both the warming of the air and the cooling of the water. A significantly smaller gradient may then result in weak circulation, and therefore in a tendency towards keeping the gradient weak.

At this point, the connection of climate regimes and small pelagic regimes still remains to be explored. Some earlier results should be remembered. First, upward (downward) trends of the RIS, indicative of periods of sardine (anchovy) predominance, tend to occur when solar activity is at relatively low (high) levels. The possible effects of high and low levels of solar activity were already discussed in connection to global climate regimes and ENSO activity; therefore, the connection of these to small pelagic regimes seems straightforward. Sardine (anchovy) populations would tend to high (low) abundance during the "weak circulation" phase, while "strong circulation" conditions would favor the expansion (contraction) of anchovy stocks worldwide (exception made for the Benguela stocks, as explained earlier).

Small pelagic regimes and global climate regimes seem to be behave in parallel but with a lag of about a decade; small pelagic variations leading global climate signals. This suggests that the regime signals are first evident at the boundary systems where small pelagics develop, and that some time is required before the signal can be detected on a truly global scale. We propose, that while variations of solar activity and resulting circulation phases may have short-term effects at the boundary systems, there would be some delay before the signal is detected within the GSAT because of the feedback mechanism linking the ENSO activity to the GSAT variations.

One consequence of the onset of a "strong circulation" phase would be El Niño events becoming stronger and more frequent as the slope of the sea level over the Tropical Pacific grows larger. More frequent and strong El Niño events would then result in a cooling of the atmosphere, assuming that, during an El Niño, $\Delta Ha = -h$ as the heat is gained by the tropical ocean ($\Delta Hw = +h$). This in turn would result in a downward trend within the GSAT. Thus, a global climate cooling trend may not be evident until enough strong El Niño events develop and the tropical ocean heat gain is large enough. A similar argument could be developed for explaining the delay between upward trends of the RIS and warming periods within the GSAT.

This hypothesis, if correct, would be an outstanding result because it would imply that variations of small pelagic stocks are an early indicator of global decade-scale changes in climate. Although a great deal of research and understanding is required before many of the conclusions and results of this work can be considered definitive, it is our feeling that the recent changes of small pelagic regimes, the late signals of global temperature trends, and the very atypical ENSO variability observed during 1990 to 1995 are all related, and suggest the following years will have both anchovy dominance and a downward global temperature on the interdecade time scale.

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